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ZONING OF ORE DEPOSITS IN AND ADJOINING THE LEADVILLE DISTRICT, COLORADO.[1]

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ABSTRACT.

The ore deposits in the heart of the Leadville district, Colorado, are divisible, as shown by Emmons, Irving, and Loughlin,[2] into two main

[1] Published by permission of the Director, U. S. Geological Survey, the Colo. State Geological Survey Board, and the Colo. Metal Mining Fund.

[2] Emmons, S. F., Irving, J. D., and Loughlin, G. F.: Geology and Ore Deposits of the Leadville Mining District. U. S. Geol. Survey Prof. Paper 148, pp. 368, 1927.

classes on the basis of mineral composition: "contact-metamorphic" silicates accompanied by iron oxides, which adjoin an obscure igneous stock, and mixed sulphides accompanied by manganosiderite and quartz gangue, which cut the "contact-metamorphic" deposits and form a broad zone extending for 2½ miles to the west and for shorter distances in other directions. A detailed consideration of the mineralogy of the mixed sulphide ore deposits clearly shows that they in turn are divisible into groups, referred to as hotter and intermediate mesothermal deposits. These groups, however, because of complications in structural control, are not ideally arranged from the standpoint of zoning.

Emmons, Irving, and Loughlin noted that barite was a conspicuous gangue mineral in certain outlying deposits on the west slope of the Mosquito Range. The junior author during 1928–1931 had an opportunity to study the outlying deposits over an area of twenty square miles, which includes mines near the heads of Iowa Gulch and Empire Gulch, and the Weston Pass district (Fig. 1), and found that these baritic deposits form a somewhat distinct outer zone in which the primary ore consists of galena and light-colored zinc blende, with small amounts of silver and practically no gold, in a gangue of barite, jasperoid, and crystalline quartz. There is also recognized a still more remote though poorly defined zone in which the same sulphides are present but jasperoid is less conspicuous and barite is practically absent, whereas dolomite is the characteristic gangue mineral. The deposits in these two outer zones are fissure-fillings and comparatively small replacement bodies. They contrast strongly with the sulphide deposits in the heart of the Leadville district and are assigned to the outer mesothermal and epithermal zones. As they have not been described before, general features of these deposits are given in some detail, followed by their relations to the deposits within the Leadville district. Analogies are also drawn with similar deposits in other districts.

In the preparation of this paper the authors have been impressed with the confusion that may result from too simple a conception of zoning. For a proper conception of Leadville, the geologist must have sufficient regard for structural conditions, must make due allowance for successive stages of mineral deposition within a small block of ground or even within a single ore shoot, and must also allow for the reactions between minerals formed at an early stage and solutions introduced during a late stage. The effects of such complications in the Leadville district might give the impression that certain minerals found in one of the inner zones were formed at relatively high temperatures, but close study of paragenesis indicates late deposition at relatively low temperatures. Again, as already stated, there is sufficient inconsistency in the distribution of certain varieties of deposits to give a confused impression of

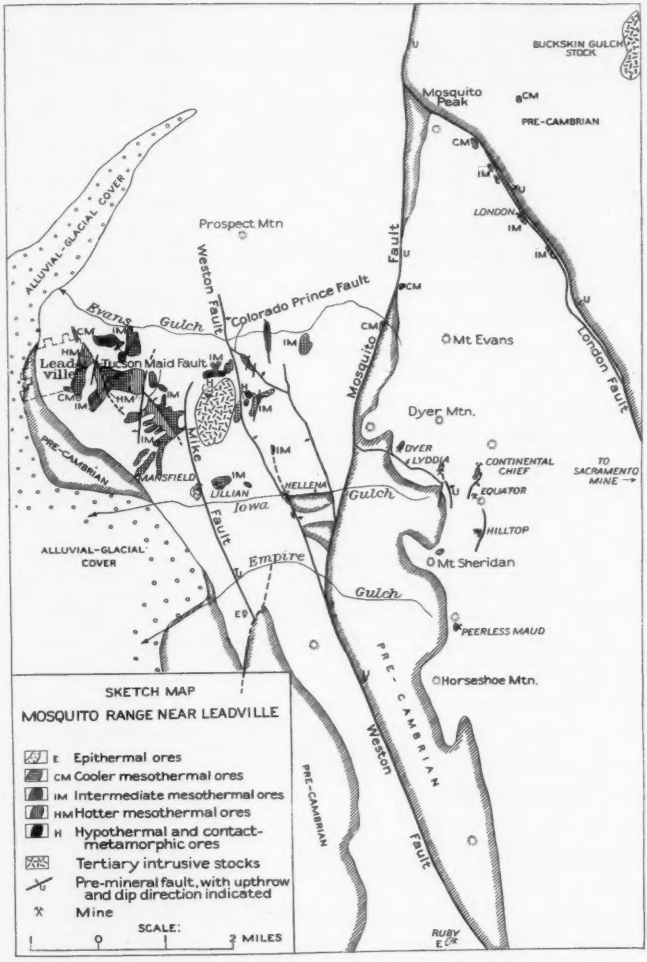


FIG. 1. Generalized sketch map of Mosquito Range near Leadville, showing location of major faults, Breece Hill plug, principal ore deposits, and mines in more distant ore bodies.

zonal arrangement unless the influence of structure on the circulation of ore-forming solutions is appreciated. The field facts give a far more complex picture than might be anticipated from a simple statement of the theory of zoning.

ACKNOWLEDGMENTS.

THE work on which this paper is based is partly the earlier field studies of Emmons, Irving and the senior author, partly that of the junior author, conducted under the auspices of the U. S. Geological Survey in co-operation with the Colorado Geological Survey Board and the Colorado Metal Mining Fund. Many of the data and suggestions, however, have come from individuals to whom acknowledgment is made in Professional Paper 148. For similar aid in the studies of 1928 and later, special thanks are due to Messrs. E. P. Chapman and Marvin Kleff of Leadville, to Mr. C. W. Henderson, President of the Colorado Scientific Society, and to those members of the U. S. Geological Survey who have been engaged in the co-operative work in Colorado. Specific references to these colleagues are made here and there, but those familiar with the recent work in Colorado will doubtless detect other influences of co-operation.

GEOLOGIC SETTING.

The results of earlier studies of the Leadville district were summarized in Professional Paper 148. Since the publication of that paper special attention has been given to questions regarding stratigraphy and structure, both in and around the Leadville district on the west side of the Mosquito Range, and in the Alma district on the east side. Some results of this work have already been published.[3] It will suffice here to present a brief summary of pertinent geologic data.

The stratigraphic sequence in the Leadville district is shown in Fig. 2. The pre-Cambrian basement and all the later sedi-

[3] Behre, C. H., Jr.: Revision of Structure and Stratigraphy in the Mosquito Range and the Leadville District, Colorado. Colo. Sci. Soc., Proc., vol. 12, pp. 37–57, 1929. Singewald, Q. D., and Butler, B. S.: Preliminary Geologic Map of the Alma Mining District, Colorado. Colo. Sci. Soc., Proc., vol. 12, pp. 295–308, 1930. Singewald, Q. D., and Butler, B. S.: Preliminary Report on the Geology of Mount Lincoln and the Russia Mine, Park County, Colorado. Colo. Sci. Soc., Proc., vol. 12, pp. 389–424, 1931.

FIG.

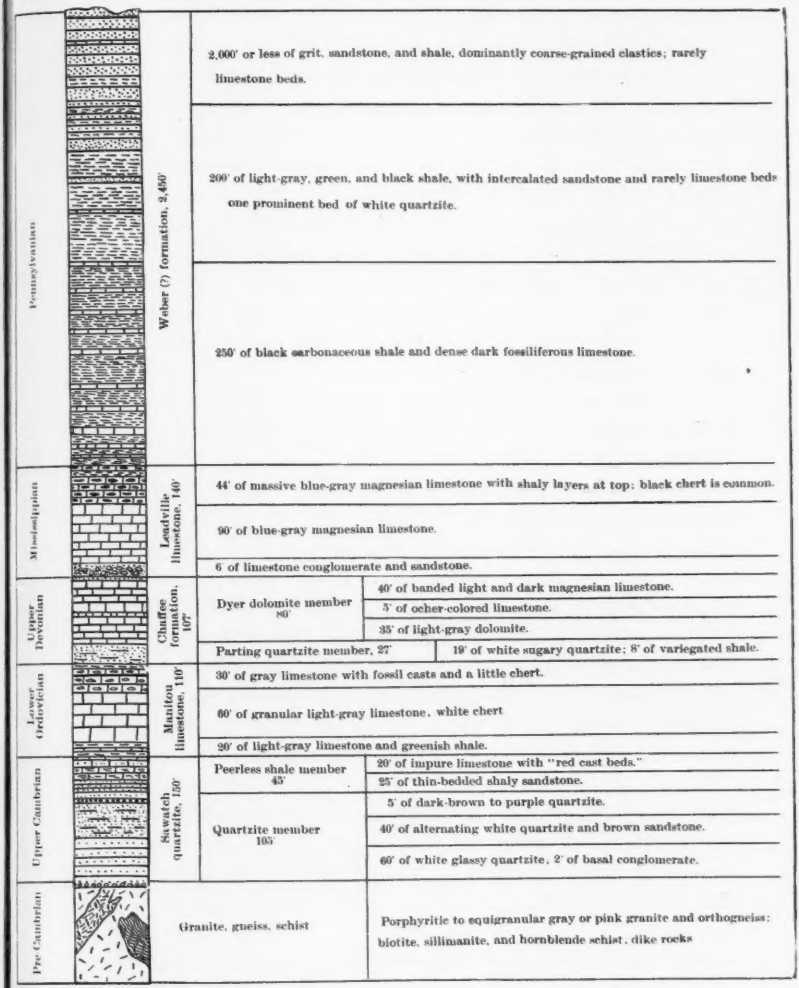

Pennsylvanian
Weber (?) formation, 2,450'
2,000' or less of grit, sandstone, and shale, dominantly coarse-grained clastics; rarely limestone beds.
200' of light-gray, green, and black shale, with intercalated sandstone and rarely limestone beds one prominent bed of white quartzite.
250' of black carbonaceous shale and dense dark fossiliferous limestone.
Mississippian
Leadville limestone, 140'
44' of massive blue-gray magnesian limestone with shaly layers at top; black chert is common.
90' of blue-gray magnesian limestone.
6' of limestone conglomerate and sandstone.
Upper Devonian
Chaffee formation, 107'
Dyer dolomite member 80'
40' of banded light and dark magnesian limestone.
5' of ocher-colored limestone.
35' of light-gray dolomite.
Parting quartzite member, 27'
19' of white sugary quartzite; 8' of variegated shale.
Lower Ordovician
Manitou limestone, 110'
30' of gray limestone with fossil casts and a little chert.
60' of granular light-gray limestone, white chert
20' of light-gray limestone and greenish shale.
Upper Cambrian
Sawatch quartzite, 150'
Peerless shale member 45'
20' of impure limestone with "red cast beds."
25' of thin-bedded shaly sandstone.
Quartzite member 105'
5' of dark-brown to purple quartzite.
40' of alternating white quartzite and brown sandstone.
60' of white glassy quartzite, 2' of basal conglomerate.
Pre-Cambrian
Granite, gneiss, schist
Porphyritic to equigranular gray or pink granite and orthogneiss: biotite, sillimanite, and hornblende schist, dike rocks

FIG. 2. Stratigraphic sequence, Leadville mining district, Colorado.

mentary rocks are cut by dikes, sills, and irregular masses of granodioritic or monzonitic rocks, locally known as the White and Gray porphyries, which were followed in the Breece Hill area by an obscurely exposed intrusive stock of originally quartz-monzonitic character but so thoroughly bleached by alteration that its identity at the surface is not readily recognized. Dikes similar to this stock in composition and probably of the same age occur elsewhere in the region. According to comparative studies with other districts all of these rocks were intruded in late Cretaceous and early Eocene time. The latest important igneous activity was the formation of plugs and dikes of rhyolite and rhyolite breccia subsequent to ore deposition and probably in Pliocene time.

Faulting took place at several different intervals. There are certain faults that can be recognized as antedating the earliest intrusions, but they are obscured and have no obvious bearing on ore deposition, and will not be referred to again. The earliest clearly recognized faulting is represented by reverse or thrust faults of north-northwest trend and steep to moderate eastward dips. This faulting accompanied folding that occurred after the intrusion of the White and Gray porphyry sills, but probably before the intrusion of the Breece Hill stock. It was accompanied and followed by minor, transverse faulting. Additional faulting in various directions took place after the thrust faulting, and after the intrusion of the stock, but before ore deposition. All the fault systems thus far mentioned exerted some control over the courses followed by ore-forming solutions. The reverse faults themselves contain ore only locally, but the shattered ground along them, especially near intersections with transverse faults and fissures, was locally replaced by ore bodies and also provided channels for ore-forming solutions, which spread along limestone beds beneath impervious covers and formed the most extensive replacement bodies or "blankets."

The latest faults, including many of the most conspicuous in the district, are normal faults, mostly of north-northeast trend and steep westward dip, that offset the ore bodies. Some of them

record a resumption of movement along pre-mineral normal faults, including "normal" movement along reverse faults.

Ore Deposits.

GENERAL STATEMENT.

On the basis of data presented in Professional Paper 148, the deposits within the Leadville district may be divided into two main classes and the second class into three or four subclasses. These classes and subclasses maintain a definite sequence of deposition and a zonal arrangement when studied with due regard to structural control, but they exhibit certain irregularities in arrangement and are not concentric with respect to any intrusive igneous mass. The first class, of little commercial interest, includes pyrometasomatic and hypothermal deposits; the second class, which includes the largest and most important deposits of the district, is mesothermal as a whole, but its subclasses represent appreciable changes in chemical composition of solutions and probably a considerable range in temperature. The third subclass may conform to the "leptothermal zone" whose recognition has been proposed by Graton.[4] The outlying deposits are for the most part closely similar to the third subclass also, but the most remote are regarded as equivalent to epithermal deposits, or to the "telethermal" deposits[5] whose recognition Graton has also advocated. Since there is a general tendency to think of the different zones in terms of depth, it is interesting to recall that all of the deposits under consideration were formed within a vertical range of a few hundred feet and beneath a cover of about 10,000 feet, as inferred by Emmons, Irving, and Loughlin,[6] although Lovering, after recent studies of unconformities in the Front Range of Colorado, thinks that the cover was little more than half as thick.[7]

[4] Graton, L. C.: The Depth Zones in Ore Deposition. Econ. Geol., vol. 28, pp. 513–555, 1933.

[5] *Op. cit.*

[6] Emmons, S. F., Irving, J. D., and Loughlin, G. F., *op. cit.*, pp. 41–42.

[7] Lovering, T. S., written communication, May, 1933.

FACIES WITHIN THE LEADVILLE DISTRICT.

Pyrometasomatic and Hypothermal Deposits.

The deposits of pyrometasomatic and hypothermal character are conveniently treated together. As a whole they are equivalent to deposits that have been classed entirely as pyrometasomatic or contact-metamorphic, but the sequence of mineral deposition and the identity of the latest minerals formed with those formed earliest in the mesothermal deposits implies the existence of hypothermal conditions in so far as they can be distinguished from pyrometasomatic conditions.

The main group of these deposits is limited to the immediate vicinity of the obscure intrusive stock at Breece Hill, and a small deposit obscurely indicated to the southwest of Printer Boy Hill at the Mansfield mine (Fig. 1). The deposits at Breece Hill are replacement bodies in limestone. Their ore minerals are mainly magnetite and specularite accompanied or impregnated by minor quantities of pyrite, chalcopyrite, zinc blende, and galena. Their principal gangue minerals are serpentine and siderite or manganosiderite, accompanied by a little wollastonite, epidote, sericite, and quartz.

This assemblage of minerals is rather confusing unless explained in a little detail. The gangue minerals of pyrometasomatic origin are wollastonite and a pyroxene or olivine which was later thoroughly altered to serpentine under mesothermal conditions. The magnetite and specularite are believed to be of hypothermal origin, and the magnetite is commonly accompanied by interstitial siderite, which, so far as definite evidence shows, began to form as the magnetite ceased forming. The siderite is believed to mark a transition from the hypothermal to the mesothermal stage. Pyrite accompanied by quartz occurs in part as irregular crystalline patches from which veinlets extend into massive magnetite, and in part as distinct veins that cut the magnetite and are similar to pyritic veins of recognized mesothermal origin. The pyrite patches may mark the close of the hypothermal stage, but it is equally if not more probable that they have replaced disseminated siderite and therefore belong to

the mesothermal stage. The other sulphides and gangue minerals are also subject to interpretation as mesothermal minerals that have impregnated the hypothermal deposits. The undoubted minerals of the pyrometasomatic and hypogene zones are shown in Fig. 3, which records the sequence of mineral deposition in the entire region.

Since most of the gold produced in the Leadville district has

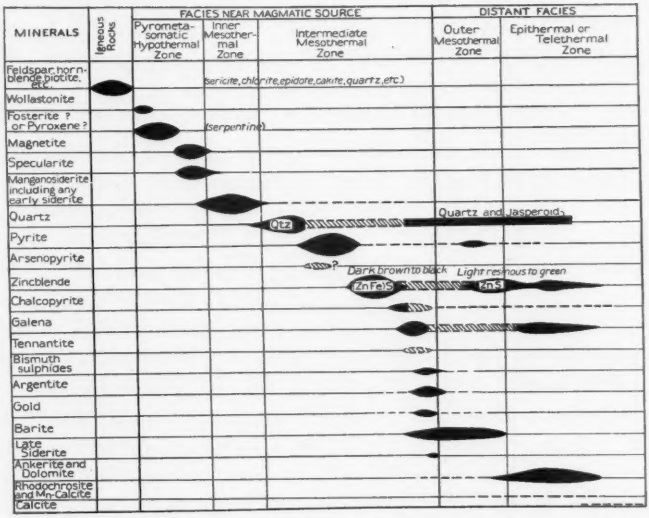


FIG. 3. Zonal classification of minerals in the Leadville and adjoining districts.

come from the Breece Hill area, it has been inferred by some that gold was characteristic of the hypothermal zone; but the magnetite ores are very low in gold and silver except where cut or impregnated by mesothermal veins composed mainly of quartz and pyrite with or without other sulphides. The bulk of the gold produced in the area has come from veins of mesothermal character.

The presence of a deposit similar to the high-temperature de-

posit of Breece Hill is indicated to the southwest of Printer Boy Hill by the existence of a small amount of serpentine and other silicates which have replaced the Leadville and Manitou limestones. The existence of an associated intrusive plug or stock has not been definitely established, but the presence of these minerals indicative of high temperatures and the occurrence of a small plug of Gray porphyry southwest of the Mansfield shaft in Iowa Gulch both suggest local conditions similar to those near the margins of the Breece Hill stock. Exposures are too poor to warrant a more explicit statement.

Mesothermal Deposits.

Deposits of the mesothermal zone, as described in Professional Paper 148, include (1) veins in siliceous rocks with associated limestone-replacement bodies, mainly in the Breece Hill area; (2) the enormous replacement bodies or "blankets" that characterize the mines of Iron, Carbonate, and Fryer Hills and extend as far west as the city of Leadville; and (3) smaller replacement deposits to the northeast and south of Breece Hill, illustrated by the Resurrection group in Evans Gulch and the Lillian mine at Printer Boy Hill. The depth and relative inaccessibility of limestones to the east and southeast of Breece Hill beyond the Weston fault and the consequent lack of their development accounts for the non-discovery of replacement bodies in those directions. The deposits indicated there on Fig. 1 are veins in siliceous rocks that overlie the limestones. The mineral composition and structural relations of the large replacement bodies close to the Tucson-Maid fault in the Iron Hill, Carbonate Hill, and Downtown areas west of the Breece Hill stock (for example, the Tucson, Wolftone, Maid, and Penrose mines) indicate that these bodies were formed near main channels of circulation and under conditions transitional between hypothermal and mesothermal. For this reason these bodies are designated "hotter mesothermal deposits." They grade into undisputed mesothermal deposits, which are designated "intermediate mesothermal deposits," since they in turn grade into still more dis-

tant facies that are designated "cooler mesothermal deposits." These three groups represent hree successive stages of deposition that are also aptly referred to as early, intermediate, and late mesothermal stages.

Hotter Mesothermal Deposits.—The deposits that can be most definitely assigned to the hotter or early mesothermal stage are characterized by large masses of manganosiderite, which have replaced both the Manitou and Leadville dolomitic limestones in the above-named mines. These masses of manganosiderite in turn were replaced in part during the intermediate mesothermal stage by small amounts of quartz and large quantities of pyrite, ferruginous zinc blende (marmatite), and galena. The manganosiderite masses are mainly developed where shattered ground served as trunk conduits for mineralizing solutions. Small amounts of specularite and magnetite[8] have been found locally in the manganosiderite and indicate temperatures favorable for the deposition of these iron oxides but evidently too high for the deposition of pyrite. The limits of the hotter mesothermal deposits are determined only by the presence of manganosiderite in large quantity, as the sulphides that have extensively replaced the manganosiderite are also abundant in the intermediate mesothermal zones.

Manganosiderite also lines small vugs in the sulphide ores that have replaced the massive manganosiderite. It has not been practical to compare the composition of this late variety with the early, but it appears that carbonates with large contents of iron and manganese can form over a considerable range of temperature, which doubtless includes the hotter and intermediate mesothermal ranges, although they were introduced in large amounts only during the hotter stage.

Intermediate Mesothermal Deposits.—Beyond the limits of the manganosiderite masses, dense replacement quartz is the principal gangue mineral, and is the principal indicator of the intermediate mesothermal zone. It occurs typically in the Cord mine and the uppermost ore shoots of the Tucson, Belgian, and other

[8] U. S. Geol. Survey Prof. Paper 148, p. 150.

mines in Iron Hill, mines in the eastern and southern parts of Carbonate Hill, and the principal mines of Fryer Hill. It occurs mainly as a floor or casing to the sulphide deposits, and is impregnated and veined to some extent by the sulphide minerals. The sulphides were thus deposited later than these masses of quartz, and no evidence has been found that would indicate their formation prior to the intermediate mesothermal stage. They occur indiscriminately, however, in both the hotter and intermediate zones, where they were deposited by replacement of carbonates, including both manganosiderite and the original dolomitic limestones. Pyrite, the earliest and most abundant sulphide, forms large, almost pure masses, mostly with too little silver or gold to be of commercial interest. It is also present in mixed sulphide ores, in which large quantities of ferruginous zinc blende (marmatite) and smaller quantities of galena were successively deposited subsequent to pyrite. E. P. Chapman [9] concludes from recent study that the blende near feeding channels contains microscopic grains of chalcopyrite, whereas blende farther from those channels does not. Thorough oxidation of the ore shoots that extended farthest from the manganosiderite masses prevents the determination of any noteworthy change in the ratio of sulphides as distance from the source of supply increases. Lead was the principal metal mined in those shoots, but the general presence of brown iron oxides and the scattered distribution of shoots of zinc carbonate point to the former presence of much pyrite and zinc blende.

A few ore shoots that have the common features of the mesothermal ores contain in addition unusually large quantities of copper, bismuth, silver, and gold. The copper is present as chalcopyrite, which was deposited later than zinc blende and at about the same time as galena. The bismuth and silver occur as bismuthinite and argentite intergrown with or replacing galena, and as one or more homogenous Bi-Ag-Pb sulphides similar to galena.[10] Gold is closely associated with these late minerals,

[9] Chapman, E. P., and Stevens, R. E.: Silver and Bismuth-bearing Galena from Leadville, Colo. ECON. GEOL., vol. 28, pp. 678–685, 1933.

[10] Chapman, E. P., and Stevens, R. E., *op. cit.*, p. 678.

and, although invisible, has amounted to as much as 14 ounces to the ton. Chapman has recently recognized free gold in this association. These minerals are later than the more abundant sulphides and, in one place at least, fill fractures in them; but so far as known they occur only in close association with common sulphides, and evidently mark the close of the intermediate stage. Late siderite forms a few flat rhombohedrons perched upon galena. Its relation to the bismuth and silver minerals is not clear.

The mesothermal veins cutting siliceous rocks in the Breece Hill area also consist mainly of pyrite, zinc blende (marmatite), and galena in a quartz gangue. Those in the Ibex, Garbutt, and Luema mines are typical. Pyrite is by far the most abundant sulphide, and most of the deposits are quartz-pyrite veins, but zinc blende and galena with their usual paragenetic relations are abundant in local shoots. Chalcopyrite is also abundant in local shoots but is interstitial to pyrite and also to zinc blende, and its quantity is likely to be underestimated. Where the pyritic veins cross dolomite or limestone beds and are not sealed with gouge, they expand into small pyritic replacement bodies that change outward into comparatively small zinc-lead shoots that are essentially identical in character with the large "blanket" deposits that have jasperoid casings.

The most noteworthy differences in composition between the large blanket deposits and the veins are the larger amounts of copper and gold in the veins. The chalcopyrite was obviously deposited later than the pyrite and blende, but is practically confined to the veins and adjacent pyritic parts of connected replacement bodies. A possible explanation for this relative abundance is that the chalcopyrite was precipitated so thoroughly by reagents within the veins, either pyrite or zinc blende or both, that very little of it succeeded in escaping from the veins into the replacement deposits.

The same general conditions apply to gold, which, where not obviously due to supergene concentration, is among the very latest of the vein minerals and is confined to the veins. It ap-

pears that the gold solutions, which rose during a late stage of ore deposition, impregnated certain permeable shoots of the pyritic ore with gold, while the shoots that were not permeable to these solutions remained essentially barren. The gold was evidently precipitated by the action of the pyrite or chalcopyrite on the solutions.

Cooler Mesothermal Deposits.—Barite in the hotter and intermediate mesothermal deposits has been found only in very small quantity as linings to small vugs in sulphide ore; but it is more abundant in the outer parts of the district—for example, in the Yankee Doodle mine on the southwest slope of Carbonate Hill, and in the Chrysolite and other mines of Fryer Hill. The few crystals found in the hotter and intermediate deposits are clearly later than pyrite and dark zinc blende (marmatite), but their relation to galena has not been determined. The barite in the outer deposits precedes sulphides. Its deposition in considerable quantity is believed, as shown in Fig. 3, to indicate conditions characteristic of the cooler mesothermal or distant facies described below. A little ankerite has also been found lining small vugs in the inner and intermediate mesothermal zones, and dolomite has been found as white crystalline patches both close to and rather remote from ore in these zones.

Distribution of the Different Mesothermal Facies.—The hotter mesothermal ores are well developed in the vicinity of the Tucson-Maid fault in the Iron Hill, Carbonate Hill, and Downtown areas, as shown in Fig. 1. The larger ore shoots that trend transversely to this fault have siliceous casings both to the east and west of the fault. There is not, therefore, a simple zonal arrangement with respect to the obscure Breece Hill stock, but local zoning is developed around the trunk channels, which are marked by intersections of the Tucson-Maid fault with transverse faults or fissures. The western limit of siliceous ore in the Downtown area has never been determined owing to the large amount of water and other difficulties that have made the cost of exploration prohibitive compared with the chances of finding ore; but to the northwest there is a large amount of jasperoid accompanied by little or no ore.

The transition of hypothermal ore into hotter mesothermal ore has already been suggested, but the hotter mesothermal deposits themselves, so far as the writers know, are not well defined on the north and east sides of the Breece Hill stock. This lack of recognition is partly because oxidation has obscured them, partly because the accessible workings are mainly in siliceous rocks, where manganosiderite is not likely to form large masses, partly because many of the workings where hotter mesothermal deposits would be expected are old and inaccessible, and partly because the problem of zoning was not adequately appreciated when the deposits were studied. The intermediate mesothermal ores, on the other hand, have been mined for 1½ miles northeast of the Breece Hill stock, beneath Evans Gulch. The ore shoots are not nearly as large as in the western part of the district, and are more siliceous. Data on their mineral composition are rather meager, but they may be regarded as transitional towards the cooler mesothermal ores, from which, according to available records, they differ in their freedom from any recognizable amount of barite.

To the south of Breece Hill, in the Printer Boy Hill area, the ores have features of the intermediate mesothermal zone as well as of transition into the cooler mesothermal zone. The arsenopyrite on the dump of the First National mine, which is now inaccessible, recalls its occurrence within the Tucson fault in the Tucson mine in Iron Hill, and suggests the presence of a local trunk channel. The Printer Boy vein contains siliceous pyritic gold ore similar to that of Breece Hill, and the Lillian mine contains narrow replacement bodies in Blue limestone, with a greater content of gold than ordinary, with local developments of the bismuth-silver sulphide intergrowth "lillianite," and with the only reported occurrence of tennantite in the Leadville district. Tennantite, from analogy elsewhere, may be correlated with the gold and "lillianite" that followed the main minerals of the intermediate mesothermal stage and were deposited in close association with them. Baritic ore, typical of the cooler mesothermal zone, was also found in the Lillian mine by J. D. Irving, though not seen in place by the writers.

A little farther to the southeast, where Iowa Gulch crosses the Hellena fault, the ores of the Hellena and adjacent mines are the most remote that can be associated with the intermediate mesothermal zone, but here too there is some confusion in mineralogy with the more distant facies of ore. The Hellena vein, which was studied by the writers in 1928, consists largely of quartz with large amounts of galena and dark zinc blende (marmatite) and smaller quantities of pyrite and chalcopyrite, listed in quantitative order. These minerals are accompanied by moderate amounts of dolomite and also calcite, some of which is manganiferous. The quartz and sulphides are typical of the intermediate mesothermal zone, but the smaller quantity of pyrite is in marked contrast to the ores of veins nearer to Breece Hill. Absence of barite also suggests the intermediate mesothermal zone, but the carbonates suggest deposition under cooler conditions. The silver content of the ore, which shows no evidence of enrichment, ranges up to 8 ounces to the ton and is generally similar to that of the unenriched veins near Breece Hill. It is not to be confused with the oxidized ores of neighboring veins and "blankets" that had very high contents of silver. Very little of the unenriched Hellena ore contained noteworthy amounts of gold, which are also lacking in some of the Breece Hill ores, although gold is the dominant metal of the Breece Hill area from a commercial viewpoint.

DISTANT FACIES OF THE LEADVILLE ORES.

The distant facies, studied by the junior author during 1928–1931, are distributed along the highest part of the Mosquito Range from the vicinity of Mosquito Peak as far south as Weston Pass (Fig. 1). They include two classes of zinc-lead ore, one characterized by baritic gangue and assignable to the cooler mesothermal zone, the other characterized by a dolomitic gangue and assignable to the epithermal zone or perhaps the "telethermal" zone of Graton.[11]

[11] *Op. cit.*

Cooler Mesothermal Deposits.

The cooler mesothermal deposits are represented by the Continental Chief, Dyer, Hilltop, Peerless Maude, and other mines. These ore deposits are replacement bodies along fissures in Blue limestone and consist of resinous to pale green zinc blende and galena, with variable though small quantities of pyrite and even smaller amounts of chalcopyrite in a gangue of jasperoid, crystalline quartz, dolomite, and barite. The content of silver in the unriched ore is only 5 ounces or less to the ton, and that of gold is negligible. Although some of the ore bodies are of considerable size, they are small and scattered in comparison with the ore bodies of the intermediate mesothermal zone. As these ores, which were only casually mentioned in Professional Paper 148, are well exposed in the Continental Chief mine, which was under development during the junior author's stay in the region, the salient features of this mine are reviewed [12] in the following paragraphs.

Continental Chief Mine.—The Continental Chief mine is situated at the head of Iowa Gulch, 2½ miles east of the Hellena mine. Its ore occurs in several replacement bodies, which are confined to the Leadville (upper Blue) limestone and are all capped by the beds of impervious shale, partly carbonaceous, and thin-bedded limestone that locally constitute the uppermost 20 feet of the formation. Although the largest ore bodies range up to 400 feet in length and 100 feet in width, they are confined to closely fissured zones, as shown in Fig. 4, and taper downward along them. Replacing action rarely extended more than three or four feet from the individual guiding fissures, and the large bodies have resulted from the coalescing of several small bodies along closely spaced fissures. In some of the smaller ore bodies, as shown in Fig. 5, the longer dimensions do not conform to the trends of steeply dipping fissures, and it appears that circulation was diverted along local bedding planes or bedding fissures.

12 Behre, C. H., Jr.: Revision of Structure and Stratigraphy in the Mosquito Range and the Leadville District, Colorado. Colo. Sci. Soc., Trans., vol. 12, pp. 51–52, 1929.

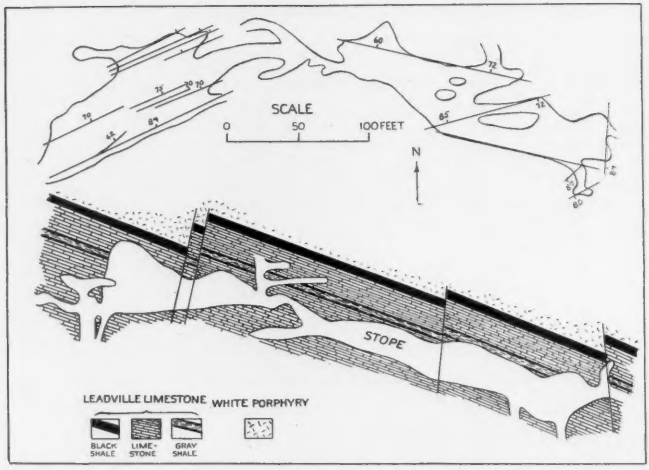


FIG. 4. Plan and section of main large-scale replacement ore bodies, intermediate and lowest ore levels, Continental Chief mine.

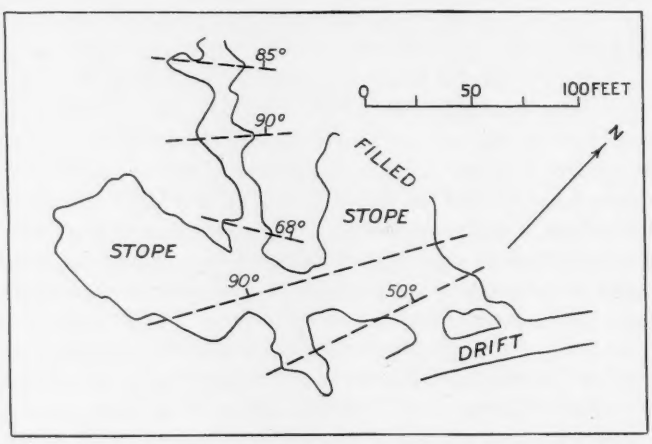


FIG. 5. Plan of stope on intermediate level, Continental Chief mine. After Colo. Sci. Soc., Proc., vol. 12, p. 51, fig. 7.

These bodies, however, are only 1 or 2 feet thick and show that replacement was as restricted along the bedding planes as it was along the steeply dipping fissures.

From the point of view of structural control as well as strength of solutions in the different zones, an instructive comparison may here be made between Fig. 6, a plan of a stope on the 8th level

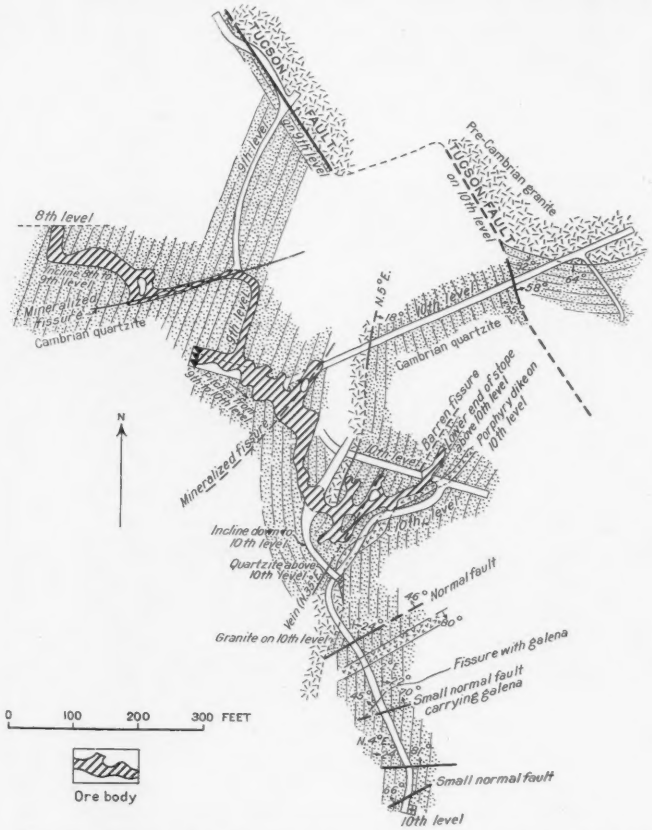


FIG. 6. Small-scale replacement veins in Cambrian quartzite, 8th level, Tucson mine, Leadville. After U. S. Geol. Survey Prof. Paper 148, Fig. 97.

in the Tucson mine, and Fig. 5. The similarity in form and even in size of the deposits shown in these two figures is striking, but the Tucson ore body is developed in difficulty replaceable Cambrian quartzite and clearly points to the work of a much more active solution chemically.

As to the mineralogy of the ore, although jasperoid is abundant, it is not as extensively developed as in the replacement deposits of the intermediate mesothermal zone. This statement needs some qualification, since prominent barren ledges of jasperoid may be found in the vicinity; but the jasperoid typical of the ore bodies in the Continental Chief mine is confined to the rock bordering the mineralizing fissures and retains the color, gross texture and structure of the original limestone or dolomite. Vugs and fractures in this jasperoid as well as in the adjacent limestone are lined or filled with quartz in poorly formed, interlocking crystals that average a quarter of an inch in diameter.

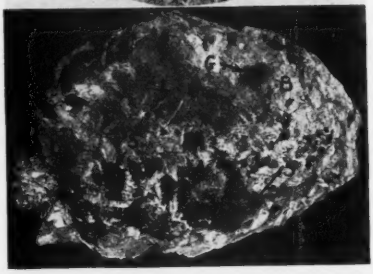
Barite, though less abundant than jasperoid, is the most conspicuous gangue mineral in the Continental Chief ore. It forms typical bladed crystals up to three inches in length, imbedded in jasperoid or in the country rock (Figs. 7, 8) and also coated with ore minerals.

Galena is the most conspicuous sulphide at present, but it may have been subordinate to zinc blende in the original ore. It presents no features that need special description. Zinc blende has largely been decomposed and is represented by a cellular or net-like residue of light gray smithsonite. The blende that remains, in contrast to that in the intermediate mesothermal zone, is mostly of light olive green color ("vetiver green, 25" YG–Y of the Ridgway color chart). Only locally in the deepest workings has dark brown blende similar to that in most Leadville ores been found. The lighter colored sphalerite does not approach the silver gray of the Friedensville, Pennsylvania, ores nor the grayish lemon yellow of those of Mascot, Tennessee, but it is nevertheless conspicuous for its light color. Inasmuch as the dark, nearly black color of the Leadville sphalerite (marmatite) is due to ferrous sulphide isomorphously intergrown with the zinc

sulphide, it is likely that the lighter colored blende with low iron content represents a lower temperature than that governing the deposition of the darker colored sphalerite.

Pyrite, which is the dominant sulphide at Leadville, is not as common as zinc blende and galena, even with due allowance for

7



8

FIG. 7. Blades of epigenetic barite in partly silicified Leadville limestone, Continental Chief mine. Blades, barite; light gray groundmass dolomite; dark spots, limonite and galena; × 20.

FIG. 8. Typical massive disseminated ore, Continental Chief Mine. *L*, limestone; *G*, galena; *S*, spongy smithsonite-sphalerite; *B*, barite.

its nearly complete oxidation to limonite. No copper sulphides, so far as known, have resisted oxidation, but a little copper is now represented by scattered stains of malachite and azurite.

In brief, the outstanding features of the Continental Chief ore bodies are as follows: (1) the ore shoots are small replacement

bodies, becoming large only where pre-mineral fissures are closely spaced; (2) the chief sulphides are galena and sphalerite, small amounts of pyrite, and negligible quantities of copper sulphides; (3) silver is of moderate importance and gold is practically absent; (4) barite especially and to a lesser extent jasperoid and openings lined with quartz are characteristic of the gangue; (5) almost all of the sphalerite is light colored.

Other Mines.—The Lyddia mine is located on the south slope of Dyer Mountain, about half a mile southwest of the Continental Chief mine. Tunnels at two levels cross the Lyddia fault, which here strikes NNE. and dips 65° WNW. The Lyddia fault brings pre-Cambrian granite on the east up against Leadville limestone on the west. As its southward continuation on Mount Sheridan contains barite, it is pre-mineral in age, but it is known to cut the South Dyer thrust fault. The ore is in the limestone hanging-wall and occurs as small replacement veins and "blankets" along pre-mineral fissures near the fault. The veins in part are capped by black shale similar to that of the Continental Chief mine. These structural relations are significant because the ore body, though blanket-like in form, is found very near a shattered zone. This deposit (Fig. 9) is less like the large-scale "blankets" of the hotter and intermediate zones at Leadville, but resembles instead the discontinuous replacements near small fissures already described for the Continental Chief mine.

The ore differs from that of the Continental Chief mine only in the much greater oxidation, cerussite being conspicuous though galena and some pyrite are still locally preserved. Barite, quartz, noteworthy amounts of limonite, and smithsonite are characteristic, together with very small quantities of copper carbonates. Assays show as much as 15 ounces of silver and $2.00 in gold to the ton, but these relatively high contents are no doubt mainly attributable to oxidation.

The location of the Dyer mine is shown in Fig. 1 but the entrance is caved. The mine was briefly described by Emmons.[13]

[13] Emmons, S. F., *op. cit.*, p. 213.

The ore on the dump shows lead sulphide, zinc carbonate, barite, and quartz in the Leadville limestone. A very small amount of malachite stains some of the ore. In all respects this ore is identical with that of the Continental Chief mine.

From the Continental Chief mine southward as far as the Equator mine, on the south slope of Sherman Mountain, there are many small prospects with essentially the same structural relations as the Continental Chief and showing closely similar ore.

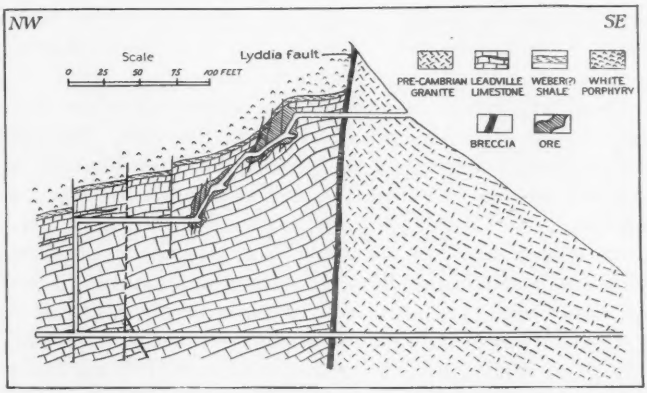


FIG. 9. Section N. 35° W. through Lyddia mine.

A shattered fault zone which is a branch of the Lyddia fault runs along the west slope of Mount Sheridan and continues southward along the crest of the Mosquito Range. It crops out at an altitude of about 13,150 feet on the west slope of Peerless Mountain, and both of its walls are of silicified Leadville limestone. Immediately to the east of this zone is the Peerless Maude mine, which consists of a group of shafts and associated tunnels. Like most of the abandoned mines and prospects at this high altitude, the workings are not accessible because filled with ice and slide rock, and no maps are available; but a general description of the workings was obtained from Mr. John Cortellini of Leadville.

The ore occurred near the top of the Leadville limestone and just beneath the thick White porphyry sill that covers the limestone. These structural relations recall those of the Continental Chief and other ore deposits of the distant facies. The ore bodies were all small and ore sufficiently rich in silver to be workable extended to depths of less than 150 feet below the surface; presumably these rich silver ores were confined to the zone of oxidation. The ore now seen on the dumps is distinctly characteristic of the cooler mesothermal zone, as it consists of relatively large amounts of barite, quartz, and galena, traces of pyrite, traces of smithsonite and calamine, stains of copper carbonates, and small amounts of anglesite and cerussite.

The Hilltop mine is situated about 1,000 feet east of the saddle that connects Mount Sherman and Mount Sheridan. The local surface geology here is not well understood, for exposures are poor and the mine workings are inaccessible. However, a low-angle fault, the West Dyer thrust, crosses from the saddle north of the Hilltop mine into the amphitheater east of the mine, and along this fault mineralization is extensive and well seen in several small openings. It is clear that the mining was carried on in the upper part of the Leadville limestone just beneath the same thick sill of White porphyry that is present at the Peerless Maude and Continental Chief mines.

Maps of the Hilltop mine furnish a further clue to its geology, but since the mine is no longer accessible interpretations must be made with reservation. The main ore bodies trended north-northeast and north-northwest and intersected approximately under the location of the boarding house which still stands on the property. As the regional strike here is northwest and the dip northeast, it is evident that the stopes, which are greatly elongated in a northerly direction, are not simply blankets but are developed parallel to sets of fissures that trend northeast and northwest and, to judge by their areal relations, are subsidiary to the West Dyer thrust. Numerous cross-cuts driven to the east and west from the productive stopes failed to locate ore. The deposits, therefore, are confined close to the fissures, implying that

the ore-forming solutions were not introduced in sufficient volume to spread for considerable distances along the bedding and form "blankets." The material on the dumps is chiefly galena, with much barite but also contains considerable smithsonite. Most of the production of the past consisted of oxidized lead-silver ore and of zinc carbonate.

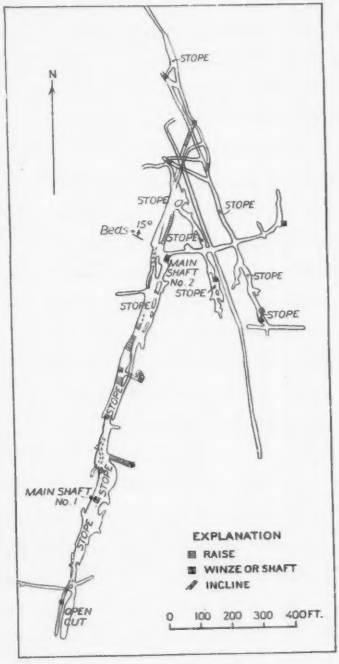


FIG. 10. Generalized vertical section of Hilltop mine. Shaded areas indicate distribution of ore.

Epithermal Deposits.

The epithermal deposits, which are represented in the Weston Pass district about 5 miles south of the Peerless Maude mine, are characterized by lead-zinc sulphide ore with dolomite as the prin-

cipal gangue mineral. Barite is absent. Jasperoid is present in the vicinity of the ore, but is only developed in small amounts in direct connection with it.

Weston Pass District.—The Weston Pass district has been described in a separate paper.[14] It includes the Ruby mine and a few smaller mines at the crest of the Mosquito Range. The deposits are all in the Leadville limestone. They are small discontinuous bodies of thinly disseminated ore formed by the impregnation of a single limestone bed. They do not occur along any conspicuous fracture zones, so far as could be determined, but their proximity to the Weston fault suggests that they were formed along a bedding fault or "slip," similar to those that are common near faults in the Leadville district.

The ore minerals best shown in the Ruby mine, include galena, which has largely resisted oxidation, smithsonite and calamine, to which the original zinc blende has been almost entirely converted. These oxidized zinc minerals have replaced the limestone of the disseminated bed and form an ore which is chiefly lead sulphide and zinc carbonate. The small amount of zinc blende that remains is surprisingly dark in color. Dolomite forms typical white rhombic crystals, which cover drusy cavities in the country rock. It is not confined to the ore bodies, but occurs plentifully in a bed immediately above the ore. It is attributed to recrystallization of the dolomitic country rock by solutions that could extract carbonaceous matter from the rock but effected no other chemical change. A little jasperoid occurs with the ore in one prospect, and a persistent ledge crops out 90 feet stratigraphically above the base of the Leadville limestone.

This outermost zone is also represented by some small deposits west of the Mike fault and opposite Empire Hill. They are near northerly trending pre-mineral faults and are accompanied by considerable jasperoid, but the sulphides and dolomite gangue are identical with those at Weston Pass.

[14] Behre, C. H. Jr.: The Weston Pass Mining District, Lake and Park Counties, Colo. Colo. Sci. Soc., vol. 13, pp. 53–75, 1932.

STRUCTURAL CONTROL AND COURSES FOLLOWED BY MINERALIZING SOLUTIONS.

In the foregoing pages emphasis on differences in mineral composition of the different classes of ore may have obscured the structural control that has determined the distribution and extent of the ore "zones." It has been incidentally stated that fractured and shattered ground along pre-mineral reverse faults and associated transverse fissures has afforded opportunities for circulation both within the Leadville district and in the outlying areas. These interlocking zones of pre-mineral faults, with due allowance for offsets along large post-mineral faults, are continuous over the entire area under consideration and can have afforded essentially horizontal courses of circulation beneath the thick cover of White porphyry and Weber(?) formation. The Breece Hill stock marks the most evident center from which such solutions might have come. It may seem improbable that solutions would travel from the Breece Hill center for 9 miles or more to deposit the ores in the Weston Pass district, even though the more distant facies are consistently arranged with respect to Breece Hill; but there is no positive evidence of any other center, except the small, obscure, and uninfluential one in Iowa Gulch. It should be clear that this statement is not intended to exclude the possibility of other, more deep-seated cupolas, however. If such others exist, they are so deep seated that only the most distant facies of ore derived from them are in evidence. This possibility, as it applies to the more distant facies, is discussed on a succeeding page.

The principal departure from a simple zonal plan is found in the most productive part of the Leadville district. To be sure the contact-metamorphic silicates and the magnetite are close by the obscure Breece Hill stock, but the largest manganosiderite deposits, which are next in order of deposition, are along the Tucson-Maid reverse fault, which trends nearly parallel to the western margin of the stock. The manganosiderite along this fault is from half a mile to 1½ miles from the western margin of the stock and merges with jasperoid upward and outward from

the fault. Some of the jasperoid, as shown in Fig. 1, is nearer the stock than is the manganosiderite. The Tucson-Maid fault, however, dips towards the roots of the stock, and, together with the transverse fissures that intersect it, has evidently provided the largest outlet for ore-forming solutions, thus accounting for the closely grouped deposits of Iron Hill, Carbonate Hill, the Downtown area, and at least part of Fryer Hill. The volume and strength of the solutions and the thorough permeability of the formations near the fault permitted the deposition of an enormous amount of sulphide minerals throughout the limestones and a conspicuous amount even in the quartzites. Workings to the northwest and south of these areas of intense ore deposition show small ore shoots and some large masses of jasperoid, and mineralization in their vicinity seems to be mainly confined to fissure zones in the relatively brittle dolomite of the Leadville (upper Blue) limestone. The relatively small amount of exploration in the more shaly and less fractured Manitou or White limestone has been disappointing, and it appears, therefore, that circulation beyond the immediate influence of the Tucson-Maid fault was essentially confined to the more open fracture zones in the Blue limestone beneath the impervious covers of porphyry and shale.

Just east of the Breece Hill stock the many closely spaced faults and fissures in the Ibex and adjacent properties afforded another large outlet for rising solutions, and allowed large quantities of them to rise through the fractured limestones into the overlying siliceous rocks. These overlying siliceous rocks, however, where not too much fractured, formed impervious barriers beneath which a considerable portion of the solutions could be diverted and forced to follow essentially horizontal courses into the outlying parts of the region.

In these outlying parts, which were several miles from the intensely fractured area, circulation became more and more confined to the relatively persistent or connected fissures in the Leadville limestone. It is true that little prospecting has been done in the Manitou limestone in this outlying country, but outcrops of the limestone are as plentiful as those of the Leadville limestone

and evidently failed to attract prospectors; furthermore, not even the fissures related to the largest ore bodies in the Leadville limestone in the outlying country have been sufficiently mineralized beneath the ore bodies to encourage development downward toward the Manitou limestone. These facts lead to the conclusion that in the outlying region, even in the fractured ground along and near reverse faults, the solutions were in too small volume and under too little pressure to force their way along any but the most open fractures. They traveled long distances without noteworthy deposition until they reached a group of closely spaced fissures in a bed or series of beds in limestone that was relatively easily replaced and lay beneath a relatively impervious cap; under such special conditions these weakened solutions had an adequate opportunity to form deposits of commercial size and grade.

The limitation of these outlying deposits to the uppermost part of the Mosquito Range is doubtless due in part, as shown in Fig. 1, to the fact that the Leadville limestone is either eroded or deeply buried in most other parts of the range. Where it remains, however, the control of deposits by pre-mineral faults is evident; for example, the Hilltop and Continental Chief ore bodies are along fissures auxiliary to reverse faults, and the Peerless ore bodies are along a mineralized branch of the Lyddia fault. These faults are connected, directly or indirectly, with the Mosquito fault, which, from the junior author's recent work, is evidently one of the largest pre-mineral faults in the region, although post-mineral movement has also taken place along it.

The great displacements along the Mosquito fault, and therefore its continuity to great depth, suggest that it may have tapped other sources of supply than that beneath Breece Hill. Such an interpretation avoids the necessity of circulation over long horizontal distances, but necessarily implies that the other sources are so deep that they are represented only by the more distant facies of deposits. This implication necessitates the further inference that the solutions from these sources, if similar in composition to those from the Breece Hill center, were able to dispose of their

large amounts of manganese and iron, represented by manganosiderite and pyrite at Leadville, while moving through the siliceous pre-Cambrian and Cambrian rocks. Such a process would be distinctly different from that associated with the Breece Hill center, and would imply either that veins of appreciable size are present along the Mosquito and adjoining faults at depth or that the minerals characteristic of the earlier stages of ore deposition were scattered in small quantity throughout a large part of the fault zone and that only the minerals of the distant facies were segregated into deposits of commercial size. Similar speculation may apply to the Weston fault, a reverse fault of great displacement near which the Ruby mine at Weston Pass is located. The failure to find ore bodies to the north of the Ruby mine along the west side of the fault may be attributed to their effective concealment beneath the cover of White porphyry and Weber (?) formation.

COMPARISON WITH NEIGHBORING DISTRICTS.

Ore deposits in and near the Alma district, on the east slope of the Mosquito Range have been described by Singewald and Butler.[15] The outstanding structural features of the Alma district are (1) the intrusive stock of Buckskin Gulch (Fig. 1), which is immediately walled by pre-Cambrian rocks that are somewhat epidotized, silicified, and pyritized; (2) the London fault (Fig. 1), a reverse fault similar in size and attitude to the Weston fault, and along which the principal gold deposits are located; (3) the Cooper Gulch (Mosquito Gulch)[16] fault, a smaller, branching reverse fault, near which a number of smaller mines are located; (4) an anticlinal flexure northeast of the in-

[15] Singewald, Q. D., and Butler, B. S.: Preliminary Report on the Geology of Mt. Lincoln and the Russia Mine, Park County, Colo., Colo. Sci. Soc. Proc., vol. 12, pp. 309, 403–404, 1931. Singewald, Q. D., and Butler, B. S.: Suggestions for Prospecting in the Alma District, Colo., Colo. Sci. Soc. Proc., vol. 13, pp. 89–131, 1933. Singewald, Q. D., and Butler, B. S.: Mines in the Vicinity of the London Fault, Alma District, Colo. (In preparation.)

[16] To avoid confusion of this local fault with the great Mosquito fault, Butler and Singewald have renamed this the Cooper Gulch fault. (Suggestions for Prospecting in the Alma District, Colo. Colo. Sci. Soc. Proc., vol. 13, No. 4, p. 101, 1933.)

trusive stock, in which another group of mines is located. Singewald and Butler recognize (2), (3), and (4) as centers of circulation and deposition, and recognize possible minor centers elsewhere, notably in the vicinity of the Sacramento mine, well to the south of the other centers (Fig. 1).

The gold deposits along the London fault are quartz veins with pyrite and other sulphides between siliceous wall rocks and are similar in character to the veins of the Ibex and adjacent mines in the Breece Hill area of the Leadville district. They represent the most intense thermal stage of ore deposition in the Alma district, but are only equivalent to the intermediate mesothermal deposits of the Leadville district. Some of the deposits east of the smaller Mosquito Gulch fault differ from any in the Leadville region in containing considerable gold with a dominantly carbonate gangue in quartzite; the others are baritic deposits in limestone, but with more carbonate gangue than the Continental Chief and similar mines on the west side of the range. Their general aspect is that of a distant facies intermediate between the outer mesothermal deposits and the epithermal deposits described on previous pages. The same comment applies to the deposits northeast of the intrusive stock and to the Sacramento mine. Old prospects in Fourmile Gulch southeast of the Sacramento mine show epithermal or "telethermal" aspects similar to those at Weston Pass.

The Alma deposits, if subjected to the same method of interpretation as those at Leadville and vicinity, present similar obstacles to a simple zonal grouping. High-temperature deposits near the intrusive stock are inconspicuous; there are no "hotter mesothermal" deposits characterized by manganosiderite; the "intermediate mesothermal deposits" along the London fault are quite as far horizontally from the intrusive stock as are the "cooler mesothermal" deposits east of the Mosquito Gulch fault, but they are along the most profound fault zone in the district, which evidently permitted the most rapid and concentrated circulation; the ultimate source of the solutions that circulated along the London fault was evidently deep-seated and may have been

beneath the intrusive stock, but such a connection is not as evident as is that of the principal deposits of Leadville with the Breece Hill stock; the Sacramento and other outlying deposits, like the epithermal facies previously described, are so remote from areas of fairly intense ore deposition that their ultimate sources and the courses followed by the solutions that formed them is also a subject for speculation.

Butler and Singewald point out that ore deposits of the Mosquito Range are mainly grouped in a broad transverse zone that trends southwestward through the Alma and Leadville districts. This feature, though evident in parts of the Leadville district, is too much involved with other local features to be as well defined as in the Alma district. Lovering [17] has demonstrated a similar structural control of ore deposits in the Front Range, and Burbank [18] has offered an explanation of similar transverse structures throughout much of the mineralized part of central Colorado. Cumulative evidence, therefore, suggests that such transverse structures, especially at their intersections with such earlier structures as the reverse faults, have afforded favorable places, first for the intrusion of igneous stocks, and later for the rise and circulation of ore-forming solutions. The lack of ideal or symmetrical arrangement of ore zones around any of the stocks is evidently attributable to local structural complexities.

West of Leadville, any possible equivalents of the more distant zones recognized east of the Breece Hill center are concealed by the deep alluvial deposits of the Arkansas Valley. Still farther west, on the east slope of the Sawatch Range, there are lead-zinc-silver deposits in the Sugarloaf and Homestake districts, but they have not yet been studied in sufficient detail to justify assigning them definitely to any of the zones recognized at Leadville. They form veins in siliceous, pre-Cambrian rocks, and in general they are moderately rich in primary (?) silver and in sphalerite,

[17] Lovering, T. S.: Preliminary Map Showing the Relations of Ore Deposits to Geologic Structure in Boulder County, Colo. Colo. Sci. Soc., Proc., vol. 13, pp. 77–82, 1932.

[18] Burbank, W. S., Ore Deposits of the Western States, pp. 277–301. Amer. Inst. Min. Eng., New York.

galena, and tetrahedrite.[19] Quartz and carbonates, rather than barite, are conspicuous gangue minerals. From available data they may be tentatively correlated with the intermediate to cooler mesothermal deposits.

COMPARISON WITH CERTAIN OTHER DISTRICTS IN COLORADO, NEW MEXICO, IDAHO, AND UTAH.

This study of the ore zones of the Leadville district has led the writers to comparisons with certain other districts in which similar ores that have replaced limestones are clearly recognizable. It is rather striking that so far as these few comparisons indicate, those districts that contain large deposits of intermediate mesothermal ores contain only rather small, scattered deposits of cooler mesothermal and epithermal character, whereas the cooler mesothermal ores have supplied the bulk of production in the others. A few of the epithermal or "telethermal" deposits are of considerable size and their similarity in mineral composition to the extensive lead-zinc deposits of the Mississippi Valley and Appalachian regions is especially noteworthy.

San Juan region, Colo.—Burbank[20] has shown that ore deposits in the San Juan region were formed in late Cretaceous or early Eocene time and also later in Tertiary time. Both groups of deposits present interesting general features but the earlier deposits especially when compared with those of Leadville,[21] present certain similarities and certain differences. At Ouray, according to Burbank,[22] deposits close by the local intrusive stock range from silicate and magnetite bodies to massive pyrite bodies with some sphalerite and galena. From one half to three quarters of a mile north of the stock, Dakota quartzite is replaced by

19 Sandberg, A. E., personal communication, 1932.

20 Burbank, W. S.: Revision of Geologic Structure and Stratigraphy in the Ouray District of Colorado, and Its Bearing on Ore Deposition. Colo. Sci. Soc., Proc., vol. 12, pp. 211, 215, 220, 1930.

21 Ransome, F. L.: Economic Geology of the Silverton Quadrangle, Colo. U. S. Geol. Survey Bull. 182, pp. 71–72, 159–160, 1901. Cross, Whitman; Howe, Ernest; and Irving, J. D. U. S. Geol. Survey Atlas, Ouray folio (No. 153), pp. 17 and 18, 1907. Burbank, W. S., *op. cit.*

22 Burbank, W. S., written communication, March, 1933.

pyrite deposits with minor amounts of sphalerite, galena, chalcopyrite, and tennantite, and with local fractures containing tetradymite, gold and silver tellurides, and native gold. From 1 to 3 miles north of the stock, veins and associated replacement deposits in Jurassic limestone consist of baritic lead-zinc ore with some silver minerals and manganiferous calcite. Five miles north of the stock the same limestone is replaced by low-grade siliceous deposits containing barite, carbonates, blende, and galena. The silicate, magnetite, and massive pyritic ores correspond to the hypothermal and intermediate mesothermal ores of Leadville, and the baritic ores to the cooler mesothermal ores; but no manganosiderite corresponding to the hotter mesothermal zone has been recognized. The rocks traversed by ore-forming solutions are much more siliceous than those in the western and outlying parts of the Leadville region, and the opportunity to form large replacement deposits of manganosiderite was therefore less favorable than at Leadville, although other unknown factors, such as the composition of solutions and the accessibility of the rocks during the hotter mesothermal stage may have been more influential, since large quantities of manganiferous siderite were able to replace siliceous rock in the Coeur d'Alene district in Idaho.

Aspen district, Colo.—Information on the ores of the Aspen district also shows certain similarities to those of Leadville, as well as certain differences. According to Bastin [23] and Knopf,[24] mineral deposition took place during one stage, but Hewett,[25] who paid the district a brief visit in 1928, found manganosiderite to be abundant on the dumps of the Little Annie and Midnight shafts and noted that at the Midnight the manganosiderite, which had partly replaced a siliceous dolomite, had been crushed and recemented by baritic material. The granodiorite stock in the southern part of the district is bordered by a contact-metamorphic

[23] Bastin, E. S.: Observations on the Rich Ores of Aspen, Colo. U. S. Geol. Survey Geol. Bull. 750, p. 49, 1924.

[24] Knopf, Adolph: Recent Developments in the Aspen District, Colo. U. S Geol Survey Bull. 785–A, p. 22, 1926.

[25] Hewett, D. F., oral communication.

zone, and the manganosiderite, also in the southern part, may, by analogy with the ores of Leadville, indicate hotter mesothermal conditions. The fact that manganosiderite escaped recognition at Leadville for many years may justify the suspicion that considerable quantities of it have been overlooked at Aspen also, but from data at hand it seems to be present only in small quantity and to indicate that the hotter mesothermal stage was not well developed.

There are also no descriptions of ores similar to the intermediate mesothermal ores that are the most abundant and important at Leadville. Spurr's descriptions and analyses [26] and the recent studies by Bastin and Knopf indicate ores similar in composition to the cooler mesothermal ores of Leadville, but richer in pearceite, argentiferous tennantite, and argentite. Knopf,[27] however, found microscopic tourmaline closely associated with sulphides, sericite, barite, and dolomite, and concluded that the deposits were transitional between the hypothermal and mesothermal classes.

The lead ore that replaces dolomite in the Smuggler Hill mine is described by Bastin [28] as low in silver and grading into rich tennantite ore. It consists mainly of dolomite and galena with a few crystals of quartz and a very little sphalerite. Its composition recalls the epithermal or "telethermal" ore in the Leadville region.

Magdalena district, New Mexico.—The Magdalena district, New Mexico, has been studied by Loughlin and its principal ore deposits are similar to those of Leadville. The development of silicates in limestone near an intrusive stock of monzonite was followed by the replacement of limestone by magnetite and specularite along minor faults for a considerable distance from the contact. Replacement bodies of sulphides were later formed in large quantity along the same faults. Massive pyrite was limited to the immediate vicinity of the stock, but large bodies

[26] Spurr, J. E.: Geology of the Aspen Mining District. U. S. Geol. Survey Mon. 31, pp. 224–226, 1898.

[27] *Op. cit.*, p. 22.

[28] *Op. cit.*, p. 44.

of zinc blende (marmatite) and subordinate galena extended for a mile from the stock. Some siderite is present in the more remote parts of these large sulphide bodies, and in the outlying parts of the district it is present in small replacement veins together with quartz, fluorite, galena, and blende. Some of these veins cut jasperoid, which in the outlying area has extensively replaced the same limestone that contains the principal ore bodies. Only a few ore shoots of appreciable size have been found in these baritic veins. No deposits referable to the epithermal zone have been recognized within the limited area studied.

Wood River Region, Idaho.—Ore deposits of the Wood River region, Idaho,[29] particularly those of the Minnie Moore mine, also bear some striking resemblances to those of Leadville, although, as at Aspen, representatives of the intermediate mesothermal group are inconspicuous. Hewett has shown that silicated limestone is replaced by manganiferous siderite, which in turn is replaced by sphalerite and cut by veinlets of quartz; also there was a widespread crushing of siderite and sphalerite before galena was deposited. Siderite, the principal hydrothermal gangue mineral, is more abundant in lodes south of Deer Creek, near the main intrusive stock, than in those north of it. Barite forms outlying veins without appreciable quantities of sulphides and with no proved genetic relation to the ore deposits.

Tintic district, Utah.—There are certain especially interesting similarities as well as differences between the ores of Leadville and its outlying districts and those of Tintic, Utah, and its outlying districts. The Tintic district[30] includes serpentinized contact-metamorphic deposits adjacent to the margin of its main intrusive stock of monzonite, but no deposits of magnetite-specularite ore have been found there. Some large bodies of limonite along the monzonite contact have been regarded as

[29] Umpleby, J. B., Westgate, L. G., and Ross, C. P.: Geology and Ore Deposits of the Wood River Region, Idaho, with a description of the Minnie Moore and nearby mines, by D. F. Hewett. U. S. Geol. Survey Bull. 814, pp. 90–98 and 230–232, 1930.

[30] Lindgren, W., and Loughlin, G. F.: Geology and Ore Deposits of the Tintic Mining District, Utah. U. S. Geol. Survey Prof. Paper, 107, pp. 282, 1919.

oxidized pyritic contact deposits,[31] but Lindgren and Loughlin referred to them as replacement deposits due to downward concentration of iron oxides derived from disseminated pyrite. In either case, they do not represent deposition at such high temperature as the magnetite and specularite at Leadville. Neither has any manganosiderite been found. There are, however, several prominent ledges of jasperoid, some close to the monzonite contact and so granular as to resemble quartzite, and others remote from the contact and of flint-like texture.

Veins in the monzonite consist mainly of pyrite and quartz, but local shoots contain in addition barite, enargite, and galena. Zinc blende doubtless was also abundant but has been mostly leached out above ground-water level, below which the mines were inaccessible. These ores, except for their enargite, are similar in composition to the intermediate and cooler mesothermal deposits of the Leadville district. The same ore minerals persist in replacement deposits in limestone for a maximum distance of about a mile from the monzonite contact. Beyond this distance barite and enargite are not present and the original ore consists of galena and blende in a jasperoid gangue. Short branches from the main ore bodies, for example in the Victoria mine, consist largely of dolomite spar, but middle layers and vugs are filled with scalenohedral calcite. Farther from the main ore bodies large amounts of scalenohedral calcite are locally present. Still farther away from the monzonite the quantity of jasperoid gangue decreases, the dolomite spar increases, and scalenohedral calcite marks the close of hypogene mineral deposition.

In the East Tintic district, 3 miles east of the Tintic ore zones, workings of the East Tintic Development Company's mine,[32] now a part of the Eureka Lily mine, showed a similar transition within a few hundred feet. The upper workings contained replacement bodies in limestone along intersecting fissures, and the

[31] Crane, G. W.: Geology of the Ore Deposits of the Tintic District. Am. Inst. Min. Eng., Trans., vol. 54, pp. 342–355, 1917. Billingsley, Paul, in Boutwell, G. M., and others, The Salt Lake Region, 16th Int. Geol. Congress, Guidebook 17, p. 117, 1933.

[32] Lindgren, Waldemar, and Loughlin, G. F.: *op. cit.*, pp. 247–248.

ore minerals were galena and blende (thoroughly oxidized to smithsonite and calamine) with a gangue of dolomite spar and some late scalenohedral calcite. On the 550-foot level, this kind of ore merged with a vein of galena and blende in a gangue of replacement quartz and barite. At still deeper levels, opened since the publication of the Tintic Professional Paper, enargite became a prominent mineral, and the ore was similar to enargite ore in the adjacent Tintic Standard mine, where the most intensive ore deposition in the vicinity took place.

In the North Tintic district, 10 miles north of the monzonite stock at Tintic, the ore bodies of the Scranton mine [33] afford an interesting parallel to those at Weston Pass, Colorado. Replacement masses of brecciated barren or low-grade jasperoid are present along certain fissures, but the main ore bodies are impregnations of limestone beds and contain very little silica. The ore is almost completely oxidized, but remnants of the original ore show galena and blende in a gangue of dolomite spar. Scalenohedral calcite is also present in its usual relations, and in the surrounding area for at least a mile from any known ore body it forms veins which are mostly barren but show a grain of galena or blende here and here and some red staining derived by the oxidation of thinly disseminated pyrite. Structural data are far too incomplete to support any suggestion that the ore at the Scranton mine was derived from the same source as the Tintic ores, but its identity with dolomitic ores of the Tintic district implies that it is a distant facies, no matter where its source may have been.

DERIVATION OF CERTAIN MINERALS.

A striking difference between the most distant facies of ore in the Leadville and Tintic regions is the practical absence of scalenohedral calcite in the one and its prominence in the other. This difference reflects differences in the country rock. In the Leadville region the Leadville limestone,[34] as is shown by a number of partial analyses, contains little or no lime in excess of the

[33] *Idem*, pp. 267–272.

[34] U. S. Geol. Survey Prof. Paper 148, p. 35.

dolomite ratio. The same statement is nearly as true for the underlying Dyer dolomite. Different beds in the Manitou or White limestone [35] contain from 1 to 19 per cent. of calcite, but were replaced by ore only in the heart of the Leadville district, and the excess calcium carbonate thus available for transportation was very small compared with the calcium and magnesium from replaced dolomite rock. In the Tintic district the older formations are prevailingly dolomitic and the ore deposits in them are accompanied by less scalenohedral calcite than those that have replaced high-calcium limestone.

This difference implies that dolomite and calcite represent material removed during deposition of replacement bodies and redeposited elsewhere. The quantities of magnesium and calcium so removed can much more than account for all of the dolomite and calcite spar in the deposits cited, and in this respect these two minerals differ from the other ore and gangue minerals. Barite, though conspicuous, occurs in such small quantity on the whole and so far from the main sources of supply that its barium could conceivably, though by no means certainly, have been leached from igneous rocks during their alteration along the hotter trunk channels that the ascending solutions followed, and redeposited when conditions permitted.[36] Silica and sulphides, however, as well as magnetite and manganosiderite, occur in such large concentrated masses and so close to the channels that are most directly connected with a deep-seated source, that the leaching of their elements from any country rock seems quite inadequate to account for them; they must, therefore, be regarded as of magmatic origin.

CONCLUDING REMARK.

The foregoing paragraph illustrates one of several factors that must be considered in a study of zoning even within one district. The main factors are the quantity and original composition of the magmatic solutions, the temperatures at which they circulate, the

[35] *Idem*, p. 29.

[36] See especially Butler, B. S.: Primary (Hypogene) Sulphate Minerals in Ore Deposits. ECON. GEOL., vol. 14, pp. 581–608, 1919.

composition and texture of the country rocks with which they have opportunity to react, and the structural conditions that control their circulation. All these factors are essential, but the writers especially emphasize structural conditions. Upon structural conditions depend (1) the speed of circulation and therefore the temperature of the solutions at any point, (2) the degree of access to the more and less replaceable rocks and consequent changes in composition and in concentration of ore and gangue minerals, and (3) the distribution of different classes of deposits into symmetrical or asymmetrical groups. Complicated structural conditions, therefore, may complicate the zoning of ore deposits so that the zones do not follow the simple concentric pattern anticipated on the basis of distance alone.

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THE RICH ORES OF GOLDFIELD, NEVADA.[1]

C. F. TOLMAN AND J. W. AMBROSE.

INTRODUCTION

RICH gold and silver-bearing ores are mostly more complex, mineralogically, structurally, and texturally, than average grade ores or lean ores from the same deposit. They commonly contain a number of rare minerals not found in the body of the ore deposit, and the inter-relation of the minerals furnishes a more complete record of the processes of mineralization, especially of the final stages during which the introduction of the larger portion of the precious metals takes place, than do the average or low grade ores.

Among the "bonanza" gold ores none are more interesting than those from Goldfield, Nevada. They are extraordinarily rich in free gold, and the relation of the gold to the other minerals is shown with diagrammatic clearness in polished surfaces (Figs. 6–10). The ore deposits are unique, according to Lindgren,[2] in their association with intensely alunitized country rock. The persistent appearance of considerable amounts of tellurium in ore analyses, in the absence of identification of any known tellurides by Ransome, led him to identify a new mineral which he named goldfieldite.

Inasmuch as the classic monograph of F. L. Ransome[3] con-

[1] Two additional papers dealing with "bonanza ores" are under preparation by the senior author and advanced students; the second describes a suite of rich ores from Kalgoorlie, West Australia, presented to the Department of Geology, Stanford University, by Mr. and Mrs. Herbert C. Hoover, and the third presents the results of the study of a suite of spectacularly rich ores from the Idaho Maryland Mine, Grass Valley, California.

[2] Lindgren, Waldemar: Mineral Deposits, p. 593, 1928.

[3] Ransome, F. L.: The Geology and Ore Deposits of Goldfield, Nevada. U. S. Geol. Surv., Prof. Paper 66, 1909.

tains no description of the ore minerals as shown in polished surfaces, and no other detailed study of the ores has been published, the senior author of this article has long hoped to obtain samples that would register clearly the complicated mineral associations and ore textures shown in specimens available to him.

Fortunately Mr. C. P. Woodhouse furnished samples of the so-called "sooty ore" which are sufficiently coarsely crystallized so that most of the complex minerals of the ore could be subjected to microscopic qualitative analysis. Also, these ores clearly picture the relation of the ore minerals to each other and to the gangue minerals, especially quartz and alunite.

The results of the microscopic study of the ores furnish conclusive data regarding the theory of the origin of the ores postulated by Ransome, and verify the existence of the mineral named by Ransome as goldfieldite, but indicate a different composition than that suggested by him, and show conclusively that gold is the last of the ore minerals (except quartz) to be introduced and that it cuts and intricately replaces older ore minerals.

The paragenesis of the ore minerals has been worked out in detail, and several minerals heretofore unrecognized in these ores have been identified.

The study also indicates that the alteration of the country rock, especially silicification, alunitization, and probably kaolinization, preceded the introduction of the ores and furnished the "available space" for ore deposition.

Ore deposition in the altered zones or "ledges" consists of a combined filling of open spaces and replacement of older minerals by later minerals. The resulting ore textures are extremely complex, and the order of deposition is not registered in the order of the concentric crusts, as suggested by Ransome, but can only be determined by the occurrence of cross-cutting veinlets and by replacement textures as shown under the reflecting microscope. Only minor occurrences of metacolloidal textures were recognized.

ALUNITE AND THE THEORY OF "SIMULTANEOUS SOLFATARISM AND OXIDATION."

The ore deposits at Goldfield are localized in portions of a few of the many ledges characterizing the mineralized area. These ledges are intensely altered fissure zones in and adjacent to dacite, which intrudes a thick series of Tertiary andesite and rhyolite breccias, tuffs, and flows.

The ledges are the result of intense silicification, alunitization, and kaolinization of the country rock, and might be likened structurally to a porous silicified sponge. At the margins of the ledges silicification is less intense, but alunitization, kaolinization, and pyritization are important. Alteration decreases away from the ledges and becomes propylitic in character with the development of epidote, chlorite, quartz, and pyrite. As indicated in Ransome's excellent maps and cross section of the ore bodies, in a very few of many scores of ledges the porous portion of the ledges functioned as an irregular tubular conduit for ore-bearing solutions, in which the rich ore was deposited as cores surrounded by zones of alteration decreasing in intensity away from the ore bodies.

This unique type of alteration and the conclusion that "the metamorphic agent was evidently a strongly acid solution carrying sulphydric and sulphuric acids and possibly sulphurous acid"[4] led Ransome to advance an hypothesis as unique as the deposits themselves; namely, that of "simultaneous solfatarism and oxidation." He states:

> In accordance with the hypothesis of simultaneous solfatarism and oxidation, it is believed that after the intruded dacite had solidified, but possibly before it had entirely cooled, the district and part of the surrounding region was subjected to stresses of unknown origin. These found relief in a very complicated system of fissures, which were unaccompanied by any considerable displacement of the rocks. Hot waters carrying abundant hydrogen sulphide with some carbon dioxide and the various metallic constituents of the ores rose in these fissures. The dissolved hydrogen sulphide was oxidized in part to sulphuric acid in the upper parts of the fissure zones and at the surface. The resulting acidic solutions percolated

[4] Ransome, F. L.: *Op. cit.*, p. 182.

down through the shattered rocks, changing their feldspars to alunite, mingling with the uprising sulphide solutions, and precipitating the greater part of their metallic load as ore.[5]

It is not necessary to summarize his detailed discussion of the reasons that led him to favor this hypothesis, especially that postulating localized acidic solutions, or how the delicate mechanism he invented could work, involving as it does the simultaneous occurrence of ascending solutions, near-surface oxidation of hydrogen sulphide forming sulphurous and sulphuric acid, descent of concentrated acid solutions against the ascending currents, and the intermingling of the hypogene and supergene solutions through a zone 1000 to 1400 feet in depth, causing the precipitation of the bonanza ores.

The crux of the question is whether or not alunite was formed before the ore minerals (except possibly pyrite) were deposited and hence the acid solutions were merely a conditioning agency preparing the pathways for the ore-bearing solutions, or whether the alunite was formed throughout the entire period of ore deposition or in the late stages only.

We believe that our studies show conclusively that the formation of alunite (and probably of kaolinite) was completed before the end of the period of pyritization and before any famatinite and later minerals were deposited.

The ore minerals followed each other in an orderly and normal sequence, clearly shown under the microscope by the spacial relations of the constituent minerals.

The ores may be classified as typical epigenetic bonanza deposits, formed both by filling of open spaces and by replacement, with the unusual feature of strong leaching and alteration of the country rock by acid solutions before the ores were deposited.

The relations indicating the early age of alunite and its replacement by the ore minerals may be summarized as follows:

1. In ores from Engineer's lease, alunite occurs as frayed inclusions in pyrite (Fig. 5).

2. In the same ores, needle-shaped aggregates of famatinite,

[5] Ransome, F. L.: *Op. cit.*, p. 196.

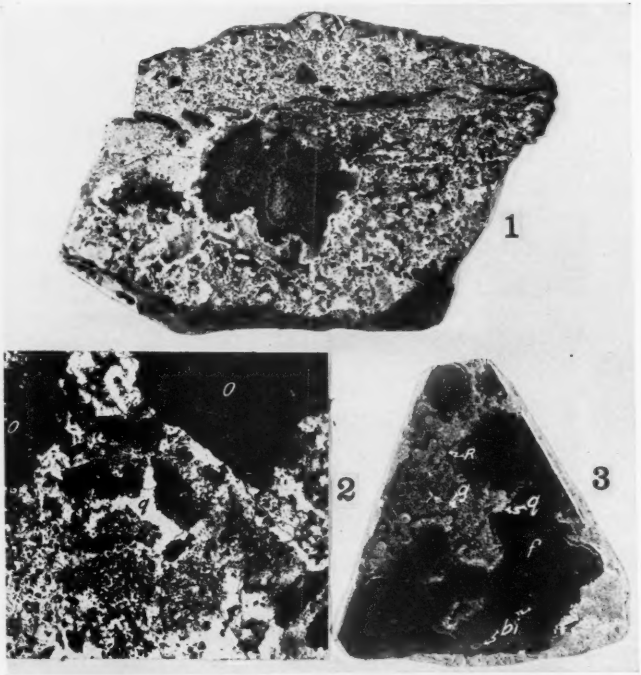


FIG. 1. Rich ore, Engineer's lease, illustrating concentric texture, interpreted as vug filling modified by replacement. Polished surface. White areas, microcrystalline quartz; gray and black, ore minerals. Dark area in center is composed of a rim of famatinite and tennantite, jet black; powdery gray material in the center is a mixture, mostly gold but with bismuthinite, goldfieldite, and famatinite intimately intermixed. Pyrite dark gray, in lower left, and in discontinuous veinlets across upper portion. ×4/5.

FIG. 2. Rich ores, Claremont shoot, 1,200 level. Polished surface. Complicated intermixture of ore minerals (*o*), with vuggy quartz gangue (*q*), which cements the sulphides. ×1½.

FIG. 3. Rich ore, Mohawk mine. Polished surface. Famatinite (*f*) surrounding sphalerite which contains aggregates of other minerals, chiefly gold (*g*). Tiny bismuthinite blebs (*bi*) are scattered through famatinite. An enlargement of one of the rosettes (*R*) is shown in Fig. 13. ×1½.

goldfieldite, and bismuthinite with small amounts of alunite (?) (kaolinite?) on their borders suggest pseudomorphing of alunite by ore minerals (Fig. 19). Also needles of alunite penetrate the above-listed minerals in the same manner that sericite commonly penetrates copper minerals but with this difference, that the points of the alunite crystals are corroded and in places are cut off flush with the ore boundaries.

3. In the same ores, pyrite apparently pseudomorphs alunite, at least it fills cavities in quartz. Small amounts of alunite (?) (kaolinite?) remain adjacent to and are included in pyrite crystals (Fig. 4).

4. In Mohawk ores frayed and irregular alunite needles occur along borders between tennantite and famatinite (Fig. 11).

5. In these ores alunite needles are entirely enclosed in single famatinite crystals, as shown under polarized light.

6. In thin section, aggregates of pyrite, forming pseudomorphs after feldspar, retain alunite needles within the aggregates.

7. Also in thin section, pyrite and famatinite are found with alunite needles bent around them as though the needles had been pushed aside by the growing crystals of the ore minerals.

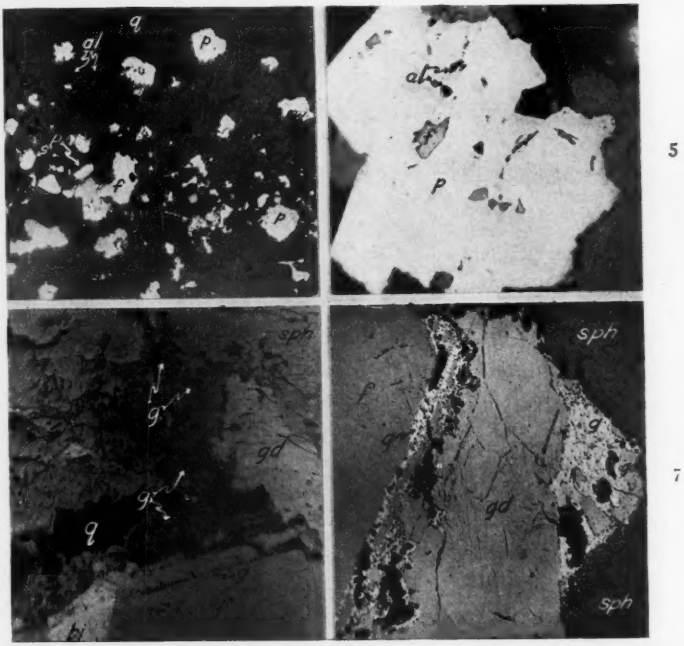
8. No alunite was discovered in veinlets cutting ore minerals, and no indication was found of the replacement of ore minerals by alunite.

MICROSCOPIC STUDY OF ORES.

Specimens Examined in this Study.

The specimens examined included examples of both rich and lean unoxidized types from several mines; viz.:

	Number of Specimens	Level	Collector
Mohawk mine	6		C. D. Woodhouse
Claremont shoot	1	1040′	W. M. Erb
Claremont shoot	1	1200′	W. M. Erb
Claremont shoot	1	860′	F. L. Ransome
Engineer's lease	1	500′	W. M. Erb
Florence mine	1	250′	F. L. Ransome
Florence mine	1		C. D. Woodhouse
New Gold Bar	1		F. L. Ransome
January mine	1		Unknown
Unknown locality	2		Unknown



4 5 6 7

FIG. 4. Engineer's lease. Pyrite (*p*) associated with alunite (*al*), in quartz (*q*). Famatinite (*f*) partially replacing pyrite, as shown by corroded remnants of the latter in famatinite and embayments of famatinite cutting pyrite.

FIG. 5. Pyrite crystal (*p*) from specimen of Fig. 4, set in quartz, with inclusions of famatinite (*f*) and alunite (*al*). Uni-terminated-quartz crystal in pyrite to right suggests precipitation of pyrite in small cavity in quartz. × 328.

FIG. 6. Mohawk mine. Gold (*g*) replacing sphalerite (*sph*) and gangue (*q*). See Figs. 8 and 9. Gold cuts goldfieldite (*gd*) in center right, and famatinite (*f*) in lower field, apparently along its crystal structure; it dies out just before entering bismuthinite (*bi*) in lower left. The right end of the veinlet has been reopened and famatinite displaced by late gangue that has come in along with it. × 44.

FIG. 7. Mohawk mine. Goldfieldite (*gd*) between famatinite (*f*) and sphalerite (*sph*). Veinlets of gold cut famatinite, paralleling border of goldfieldite, and gold replaces goldfieldite in center right. Jet black is gangue. × 55.

Texture of Rich Ores.

The texture of the rich ores as seen in hand specimens is shown in Figs. 1–3, and by Ransome in Plates XXIII–XXV. Briefly, it varies from a massive finely crystalline type in which the ore minerals are disseminated through the gangue in discontinuous aggregates of variable size (Fig. 1) through vuggy types (Figs. 1, 2) to massive "sooty" specimens which are practically solid ore minerals (Fig. 3).

As was emphasized by Ransome, the vuggy types were developed by profound alteration of the country rock, particularly within the ledges, that changed the dacite to a mass or web of porous microcrystalline quartz and altered the feldspars completely, commonly to aggregates of alunite and/or kaolinite. Such vuggy country rock containing bunches of easily replaceable alunite and kaolinite proved to be an excellent host for the ore minerals.

The ore minerals were deposited partly as linings in these vugs, probably precipitated directly from the mineralizing solutions. However, the vugs are rarely completely filled by ore minerals; the remaining vugs are lined by uniterminated quartz crystals Such vug filling has resulted in what appears to be a succession of minerals, one laid upon the other. A common succession in such crusts is gangue, gold, goldfieldite; or gangue, gold, sphalerite; or gangue, gold, famatinite. In hand specimens this has every appearance of successive crusts, making gold earlier than the supposed superposed minerals. However, this is not the case, for under the microscope gold is seen to be replacing either one or both, usually both, of the adjacent minerals. Thus, gold is really the latest in these series, though commonly occupying an intermediate position in the crusts (Figs. 1, 2, 6–10). Evidently the process of mineralization has been a complicated combination of successive precipitations in open vugs, accompanied and modified by replacement by late ore minerals of both gangue and early ore minerals.

No textures that could be interpreted as metacolloidal were observed, with the possible exception of that developed by the

gold-silver tellurides in Claremont ores (Fig. 18). The concentric arrangement there shown can possibly be interpreted in several ways, but from the cross-cutting relationships these tellurides bear to other minerals, it seems probable that they have partially replaced earlier minerals, chiefly bismuthinite. Their relations to one another may be explained as due either to unmixing or to successive introduction, one after the other.

Gangue Minerals.

The gangue minerals examined in thin section are: quartz, chalcedony, alunite, kaolinite, zircon, epidote.

The detailed mineralogy and associations of these gangue minerals in the ores have been fully discussed by Ransome and will not be repeated here. The presence of alunite makes these deposits unique amongst bonanza ores of this type, and the explanation of its presence is one of the most difficult questions to be answered in connection with the genesis of the ores.

Deposition of silica was probably more or less continuous throughout the mineralization and continued after all the metallic minerals were deposited, as evidenced by crustification along veinlets cutting through the ore. Commonly, such crusts formed of euhedral uniterminated quartz crystals have ore minerals along their crests, with second crusts of quartz in turn built upon the ore minerals. Every open vug examined was lined by a crust of quartz crystals. Reopened veinlets and new fractures through the ore are filled by crustified quartz.

Fissuring and brecciation of the ore were recurrent throughout, and also followed the period of ore deposition. Irregular veinlets of gold that intersect the earlier minerals are characteristic. Some of these veinlets have been reopened, as indicated above, the gold film broken and displaced, and late silica deposited along them. In fact, some of the richest ores from Mohawk mine have been so completely crushed and pulverized that they might be considered as a type of mylonite.

Ore Minerals.

The ore minerals recognized in the rich ores are: pyrite, marcasite, sphalerite, wurtzite, tennantite,[b] famatinite, bismuthinite, goldfieldite,[a] unknown mineral intergrowth of two minerals,[b] sylvanite,[a] hessite,[b] petzite,[a] yellow gold, carrying silver, red gold, low in silver.

Pyrite.—Pyrite, commonly associated with alunite, is widely disseminated and characteristic of all but the very richest ores examined. Cubes, pyritohedrons, and anhedral grains in clusters, pseudomorphic after feldspar or hornblende phenocrysts,[6] or more commonly with irregular outlines, are abundant. Such clusters are commonly arranged in more or less continuous bands. Further, single crystals of pyrite have developed peculiar elongated or irregular (in one case skeletal) outlines in quartz, mostly with small amounts of alunite within them. Some of these relations are shown in Figs. 4 and 5. The suggestion is everywhere apparent that, although their periods of formation may have overlapped to some extent, pyrite continued to be deposited after the formation of alunite was completed.

Pyrite and gold are rarely close associates. However, in specimens from both Engineer's lease and Mohawk mine, tiny inclusions of pyrite are found in both "yellow" and "red" gold. The proved replacement origin of gold (Figs. 6–9) suggests that the dust-like swarms of inclusions of pyrite, famatinite, and other minerals in the "red" gold (Figs. 16, 17) are the residuum after nearly complete replacement. However, the heterogeneous character of these micro-inclusions makes this explanation difficult of acceptance.

Marcasite.—Marcasite, readily distinguished from pyrite by means of polarized light, is present in minor amounts. No dif-

[a] Previously suspected, here confirmed; [b] not previously reported.

[6] The majority of the dacite phenocrysts are changed to aggregates of alunite and/or kaolinite. As shown by Ransome, their original nature can be recognized from a comparison with phenocrysts in unaltered dacite. Where pyrite grains form the pseudomorphs, the pyrite may have replaced phenocrysts directly, or it may have replaced alunite-kaolinite pseudomorphic aggregates. The retention of small amounts of alunite and/or kaolinite within the pyrite aggregates makes the second interpretation seem more probable.

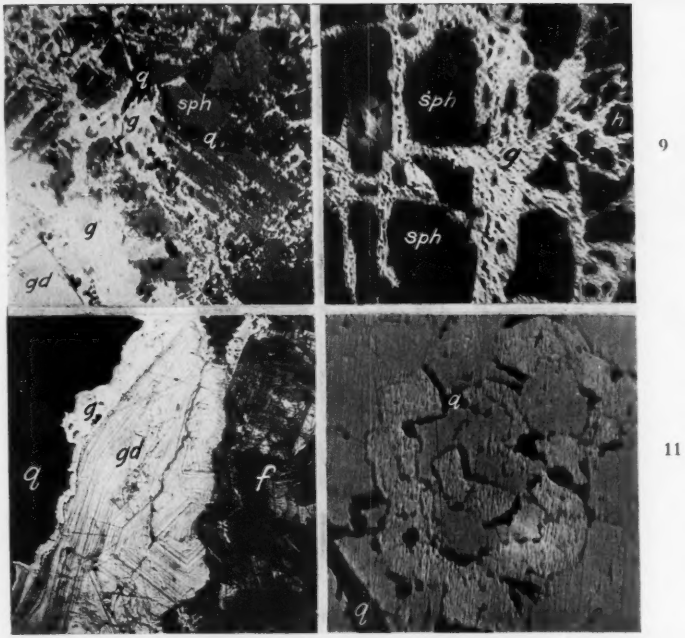


FIG. 8. Enlargement of portion of Fig. 6. White, gold (*g*), cutting and replacing sphalerite (*sph*) along crystallographic directions. Gold cuts goldfieldite (*gd*) in lower left. Gangue (*q*) has also been attacked to some extent by gold. × 157.

FIG. 9. Mohawk mine. Gold (*g*) cutting sphalerite (*sph*) along a somewhat regular pattern. The feather edges of gold, combined with cross-cutting veinlets surrounding corroded residual fragments of sphalerite, indicate replacement of sphalerite by gold. Black areas (*h*) are holes. × 122.

FIG. 10. Mohawk mine. Etch patterns developed on goldfieldite (*gd*) and famatinite (*f*) in 25 seconds with KCN, with greater rapidity (note darker color) on famatinite. The patterns in goldfieldite are considered to be growth patterns. Gold (*g*) apparently has been guided by these growth lines as it came in between goldfieldite and gangue, replacing both. × 61.

FIG. 11. Mohawk mine. Irregular aggregates of tennantite crystals (*t*) surrounded by famatinite (*fm*) with gangue (*q*) along boundaries. In polarized light famatinite crystals are seen to grow out from tennantite boundaries, indicating famatinite to be the later of the two. × 61.

ferences in mode of occurrence between marcasite and pyrite could be determined; all remarks made in connection with the latter mineral are believed to apply equally well to the former.

Sphalerite.—Sphalerite was previously reported as occurring in small amounts, mostly as colloform crusts over other sulphides In ores here examined from the Mohawk mine, sphalerite is abundant. Microchemical tests indicate that it carries appreciable amounts of iron.

Sphalerite has been extensively replaced by gold. As shown in Figs. 6, 8, and 9, gold intersects sphalerite in a myriad of veinlets, many of which appear to have been controlled by the crystal structure of sphalerite, giving the mesh of gold a geometrical pattern. Under high magnification, these veinlets of gold have beautifully developed feather edges, tiny stringers and tongues of gold project into sphalerite, and these relations leave no doubt as to the relationship between the two.

Although replaced by gold with extraordinary ease, sphalerite has not been replaced to any extent by any other mineral. It is cut by rare veinlets of goldfieldite, and is therefore, one of the earlier minerals. It has to some extent replaced pyrite or gangue adjacent to it and is, therefore, considered later than that mineral and earlier than goldfieldite or gold. It may be contemporaneous with tennantite and famatinite.

Wurtzite.—The hexagonal zinc sulphide, wurtzite, was identified in Goldfield ores by Ransome in 1914.[7] He found it closely associated with sphalerite, forming colloform crusts over other minerals, and considered it to be probably secondary.

In the specimens examined in this study, wurtzite was found only in specimens from the Claremont shoot, 1200 foot level. Although it appears identical with sphalerite in reflected light, it is clearly anisotropic under crossed nicols. Crushed fragments are dark reddish brown, pleochroic from yellow brown to reddish brown. They show a moderate birefringence. Michrochemical tests confirmed the presence of zinc and iron.

From its relationships to other minerals, the wurtzite in this

[7] Ransome, F. L.: Wurtzite at Goldfield, Nevada. Wash. Acad. Sci., vol. 4, pp. 482–485, 1914.

specimen is undoubtedly primary. It has ragged borders against goldfieldite and apparently bears the same age relationships to other minerals as does sphalerite. Its presence as a primary mineral checks the deduction that acid conditions prevailed during mineralization, as indicated by the presence of marcasite and alunite.

Tennantite, $Cu_3SbS_3 + x(Fe, Zn)_6As_2S_9$.[8]—An isotropic mineral that reacted for copper, iron, arsenic, and sulphur, bluish in contact with famatinite, and gave etch tests for tennantite, as outlined by Short, was identified as that mineral. It is present in considerable amounts in ores from Mohawk mine, Claremont shoot, and Engineer's lease, and in small amounts in all ores examined. It is difficult to distinguish from famatinite in ordinary light, and since these two are invariably associated, this may account for its having been overlooked in the past.

There is no evidence of famatinite having replaced or cut tennantite. In polarized light it is apparent that famatinite crystals have grown out from and around areas of tennantite in most cases. Their periods of deposition may overlap, but precipitation of famatinite is believed to have continued after the formation of tennantite was completed.

The presence of euhedral crystals of alunite along contacts between the two minerals and as inclusions in both famatinite and tennantite indicates clearly that the formation of alunite was complete before deposition of either of those minerals (Fig. 11).

Famatinite, Cu_3SbS_4.—An analysis of Goldfield famatinite given by Ransome (see Table I), indicates it to be intermediate in composition between theoretical luzonite (Cu_3AsS_4) and theoretical famatinite (see above), though somewhat low in sulphur.[9]

[8] Prior, G. T., and Spencer, L. J.: The Identity of Binnite with Tennantite; and the Chemical Composition of Fahlerz. Miner. Mag., vol. XII, p. 202, 1900. Formula as given by Farnham, C. M.: Determination of the Opaque Minerals, p. 119, 1931, is $Cu_{10}(Cu, Fe)_2As_4S_{13}$.

[9] Schneiderhöhn and Ramdohr (Lehrbuch der Erzmikroskopie, II Bd., p. 468) consider material of such composition, which exhibits multiple twinning in polarized light with crossed nicols, to be an intergrowth of two minerals, stibioluzonite and famatinite. This is based on their determination that multiple twinning is never developed in typical famatinite, although it is highly characteristic of stibioluzonite.

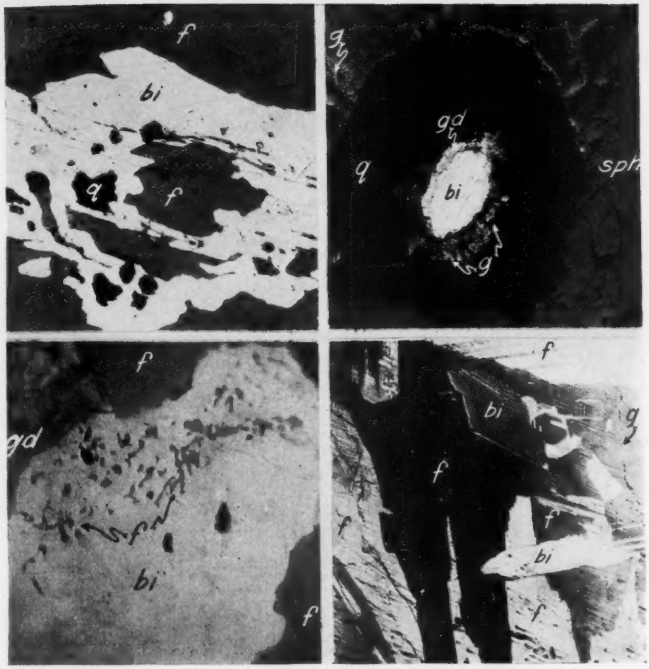
Famatinite is the predominating mineral in all the ores examined. In ordinary reflected light its characteristic pinkish gray color makes it one of the easiest minerals to recognize. In addition, because of its highly anisotropic nature, this mineral lends itself to careful examination under polarized reflected light. Beautiful twinning effects in individual crystals, which combine to form an intergrown mass, give a kaleidoscopic play of color on rotation of the stage. The crystals as thus revealed are anhedral and vary greatly in size (Fig. 15).

Famatinite is invariably associated with bismuthinite, goldfieldite, and gold, and commonly contains small areas of tennantite. Veinlets of gold, and more rarely of goldfieldite, cut famatinite. Many of these veinlets are so tiny that they are visible only with highest magnifications. Commonly they cut at random across crystals of famatinite (Fig. 15), but along contacts of famatinite with goldfieldite the veinlets roughly parallel the contacts, being controlled by the crystal structure of the famatinite.

Scattered bismuthinite blebs are included in larger crystals of famatinite (Fig. 15). The peculiar outlines of some of these blebs in famatinite (Fig. 12) are shown by polarized light to be probably due to crystallographic control of famatinite on bismuthinite. The large fragments of famatinite within such blebs may be oriented with one another and with the neighboring famatinite crystals. Taken with other relations (Figs. 14, 15), *i.e.* random intersection of famatinite crystals by bismuthinite and tiny inclusions of famatinite crowding bismuthinite crystals, partial replacement of famatinite by bismuthinite is strongly indicated but not proved. Bismuthinite is certainly later, at least in part, than famatinite.

Summarizing, famatinite is earlier than goldfieldite or gold, is earlier than some bismuthinite, and probably overlaps with tennantite and sphalerite, the latter two being earlier in part.

Bismuthinite, Bi_2S_3.—In ordinary reflected light, white blebs or needles of bismuthinite scattered through famatinite are conspicuous in rich ores from all localities. Typical occurrences of this mineral are shown in Figs. 12–15, and 18. Its relations to famatinite have already been discussed.



12 13

14 15

FIG. 12. Mohawk mine. Bismuthinite (*bi*) included in famatinite (*f*), with fragments of residual gangue (*q*). The peculiar outlines of bismuthinite are due either to replacement of one mineral by the other or to vug filling in famatinite by bismuthinite. In either case bismuthinite is younger. Polarized light proves that the included famatinite areas are oriented with the areas enclosing bismuthinite. × 174.

FIG. 13. Mohawk mine. Rosette of gangue (*q*) set in sphalerite (*sph*) with crystal of bismuthinite (*bi*) in center surrounded by a thin band of goldfieldite (*gd*). Gold (*g*) replaces a portion of the gangue and cuts sphalerite in veinlets, particularly well shown in the upper left. An example of complex vug filling and replacement. × 48.

FIG. 14. Mohawk mine. Bismuthinite crystal (*bi*) containing blebs of famatinite (*f*), which may be due to unmixing or may be residuals left by replacement by bismuthinite. Bismuthinite is bordered by famatinite and goldfieldite (*gd*). × 415.

FIG. 15. Mohawk mine. Polarized light with nicols crossed. Bismuthinite (*bi*) included in famatinite (*f*) crystals. The upper bismuthinite crystal is in extinction position. Twinning is shown in famatinite in the upper and right-hand parts of the field. A veinlet of gold (*g*) cuts across famatinite in left field and another in right field, without regard to crystal outline or structure. × 55.

Though most commonly associated with famatinite, bismuthinite is also associated with goldfieldite. Tiny veinlets of the latter mineral intersect bismuthinite blebs and, as shown in Fig. 13, goldfieldite commonly forms a band around bismuthinite, separating it from adjacent minerals. Bismuthinite is thus earlier than goldfieldite and has been replaced by it to some extent.

In addition to goldfieldite, hessite, petzite, and sylvanite have selectively replaced bismuthinite (Fig. 18). These tellurides, particularly the gold-silver tellurides, have followed irregular fractures through bismuthinite, and in places have apparently widened the fractures into rounded patches by replacement. Such selective replacement of bismuthinite by tellurides is obvious throughout the suite, although why bismuthinite should be so readily attacked by tellurium minerals is not understood.

Where the telluride-bearing veinlets extend beyond bismuthinite, the veinlets are almost invariably filled with gold, usually to the total exclusion of tellurides. Since the gold-silver tellurides and gold are probably contemporaneous, the suggestion is apparent that bismuthinite acted as the precipitating agent for the tellurium-bearing minerals dissolved in the last ore-precipitating solutions.

Goldfieldite, $Cu_6Sb_2(S, Te)_9$ *(?).*—Goldfieldite, first identified by Ransome,[10] has been considered by Dana,[11] Short,[12] and others to be probably a mixture of famatinite and other minerals. This investigation has shown that there is undoubtedly a new mineral

[10] Ransome, F. L.: *Op. cit.*, p. 116.

[11] Dana: Textbook of Mineralogy, 3d Ed., p. 391.

[12] Short, M. N., personal communication, August 24, 1933.

Short examined Ransome's original specimens of goldfieldite in 1924 and concluded the mineral was a mixture. Only the excellent Mohawk mines specimens, supplied by Mr. Woodhouse, prevented the authors from reaching the same conclusion, so intimately are all the minerals intergrown in all but the richest "sooty" ores. Ransome (p. 196) considered such sooty ores to be "a mixture of attrition material and sooty sulphide mixtures of no definite mineralogical character. They are probably due to recent enrichment by the chemical action of the present groundwater." However, this study has shown that these ores are of hypogene origin. In them the different minerals are not so confusedly intergrown and are present in large enough crystals and crystal aggregates to make determinations relatively simple and diagnostic. Once recognized, it was, of course, a fairly simple matter to determine each where present in other more complex relationships.

present in these ores, quite distinct from famatinite or any other of its associates. This mineral is believed to be the goldfieldite of Ransome's preliminary description. Because of the importance of this identification the main portions of the detailed discussion accompanying the original identification are quoted:

Goldfieldite:

At the time of the second visit to the district, in 1908, specimens were secured of the dark tellurium and gold-bearing material from the Mohawk mine for the purpose of determining its mineralogical and chemical character. A piece of rich ore from the Mohawk Combination lease . . . was broken up and the fragments of the dark telluric crust picked as free as possible from the gangue. These were crushed to pass through a 40-mesh screen and freed from fine dust. The grains were picked over several times under a lens and a separation effected into (1) yellow grains, (2) gray grains, and (3) mixed grains and gangue. The yellow grains proved to be marcasite.

The gray portion when examined under the microscope appeared homogeneous with the exception of a few minute specks of gold embedded in the gray mineral. The latter is a dark lead gray with a high metallic luster. It is brittle, breaks with a conchoidal fracture, and has a hardness of 3 to 3.5, although on account of the brittleness of the material it appears to be somewhat softer when crushed. No crystal faces have been detected. The small quantity of purified material, only 1.2 grams in all, was analyzed by Doctor Palmer with the following results:

Copper	33.49	Gold	0.51
Sulphur	21.54	Silver	0.18
Tellurium	17.00	Gangue	2.00
Antimony	19.26		
Arsenic	0.68		101.57
Bismuth	6.91		

Of the gold about 0.40 per cent. in terms of the whole analysis is combined, presumably with tellurium, and 0.11 per cent. is native.

As bismuthinite is a common mineral in these ores, the possibility that the material analyzed might be an intimate mixture of bismuthinite with some other mineral has been considered. If the analysis be calculated in molecular proportions, and the constituents of bismuthinite be subtracted (Bi_2S_3), the following molecular quantities remain.

Cu	0.527	As	0.009
S	.624	Au	.002
Te	.133	Ag	.001
Sb	.100		

While determinative work on minerals such as the sulphantimonites, which rarely show crystal form and are often intergrown with other minerals, is as a rule more or less unsatisfactory, there seems to be no escape from the conclusion that the present mineral is a new species. It is provisionally so regarded and "goldfieldite" is suggested as an appropriate name.

Since apparently no further work was done on this mineral, no etch tests established, or examination of the mineral in polished surface made, the present authors were in some doubt as to its positive recognition. However, by a process of elimination the search was narrowed down to a gray, brittle mineral, hardness 3 to 3.5, which breaks with a conchoidal fracture and takes a high polish. This mineral does not correspond either in physical properties or chemical composition with any known mineral; it is undoubtedly a new species. Thus, although without having had the identification confirmed by Ransome, this new mineral is believed to be goldfieldite and is so considered throughout this paper.

Although present in all ores examined, no area large enough to allow collection of a sample for quantitative chemical analysis was found, so intimately is it intergrown with famatinite, bismuthinite, gold-silver tellurides, and gold. However, free areas large enough to allow collection of pure material for microchemical tests are easily found.[13] Repeated qualitative tests of this sort confirmed the presence of copper, antimony, tellurium, and sulphur. No arsenic was found in any of the samples tested. Its presence in the original preliminary analysis is believed to have been due to contamination of the sample analyzed by famatinite.

Although goldfieldite occurs in relatively small amounts, intimately associated with other minerals, famatinite is abundant, and large fragments practically free from contamination are readily obtainable. Ransome's analysis of this mineral may therefore be accepted with confidence. This analysis is shown in

[13] Microchemical procedure and tests used throughout this study followed as closely as possible the methods outlined by M. N. Short (The Examination of Opaque Minerals: U. S. Geol. Surv., Bull. 825, 1931). The presence of tellurium made it difficult to obtain clear-cut tests for antimony. Supplementary blowpipe analysis confirmed the suspicion that this element is present in notable amounts.

Table I, both in percentages and reduced to molecular proportions. The preliminary analysis of goldfieldite and the molecular proportions are also shown. Then, assuming all the arsenic appearing in the analysis of goldfieldite to be due to contaminating famatinite, proportionate amounts of the other constituents are subtracted. All gold and silver is figured as tellurides and all bismuth as bismuthinite.

TABLE I.

	Famatinite		Goldfieldite		Famatinite to be Subtracted from Goldfieldite	Gold-Silver Tellurides		Bismuthinite	Final Mol. Proportions Goldfieldite	
	Analysis	Mol. Prop.	Analysis	Mol. Prop.		Syl.	Petz.		Mol. Prop.	Mols.
Cu	48.0	.750	33.49	.527	0.046				.481 6	−.005
Sb	11.0	.100	19.26	.160	0.006				.154 2	−.008
Te			17.00	.133		.003	.002		.128 } 9	
S	28.8	.900	21.54	.673	0.055			.049	.569 }	
As	12.2	.147	0.68	.009	0.009					
Au			0.51	.002		.001	.001			
Ag			0.18	.001		.0005	.0005			
Bi			6.91	.033				.033		

The final proportions, as shown in the last column above, correspond approximately to the formula $Cu_6Sb_2(S, Te)_9$ or $6CuS.Sb_2(S, Te)_3$. Goldfieldite thus appears to be essentially a copper sulphantimonate with part of the sulphur replaced by tellurium. Beegerite ($6PbS.Bi_2S_3$), luzonite ($6CuS.As_2S_3$), and high sulphur famatinite ($6CuS.Sb_2S_3$) have analogous formulæ.[14] The formula for the fahlerz group is of especial interest in this connection. Prior and Spencer[15] consider this group to be essentially $3R'_2S.R'''_2S_3 + x(6R''S.R'''_2S_3)$, where $R' = Cu, Ag$; $R'' = Fe, Zn$; $R''' = Sb, As, Bi$; and x is a small fraction, usually less than ½. It may be that, being isometric, goldfieldite is more nearly analogous to the $6R''S.R'''_2S_3$ member of this formula than it is to beegerite, luzonite, or high sulphur famatinite, the last two of which are orthorhombic, whereas the first,

[14] Wherry, Edgar T., and Foshag, William F.: A New Classification of the Sulphosalt Minerals. Jour. Wash. Acad. Sci., vol. 11, no. 1, pp. 7–8, Jan. 4, 1921.

[15] *Op. cit.*, p. 202.

isometric according to Wherry and Foshag, is strongly anisotropic according to Schneiderhöhn.

In order that its recognition may be facilitated in the future, the determinative characteristics may be summed up as follows (after the system of Farnham):

Description: Isometric. Massive; no cleavage detected; no crystal faces detected; conchoidal fracture; brittle. H.: 3 to 3.5. Metallic luster. Black or dark gray in color.

Composition: $6CuS.Sb_2(S, Te)_3$ or $Cu_6Sb_2(S, Te)_9$. A copper sulphantimonate, with part of the sulphur replaced by tellurium.

Micro.: Reagents: Conc. HNO_3 fumes bleach, drop stains brown; rubs pale brown. Conc. HCl may stain faint brown, practically negative; KCN stains brown and etches rapidly, developing scratches and crystal structures (see Fig. 10); $FeCl_3$, KOH, $HgCl_2$, neg.

P. L. (Polarized light): isotropic.

Color: Grayish white with faint brownish tinge, practically identical with tetrahedrite, darker than bismuthinite, and lighter than sphalerite.

Hardness: Medium. With no pressure, needle makes a light scratch.

The typical occurrence of goldfieldite in the Mohawk ores is shown in Figs. 6, 7, and 10. It occurs between famatinite and sphalerite, as rims about bismuthinite, and as veinlets cutting across any of these minerals. In the ores from Claremont shoot, goldfieldite is present in about equal amounts with famatinite, which it has partially replaced. In the specimen of Fig. 1 from Engineer's lease, famatinite, bismuthinite, and goldfieldite appear to have selectively replaced alunite, or, since they are different in age, the first two may have been the ones to attack alunite, being later partially replaced in turn by goldfieldite. These relations are shown in Fig. 19.

As may be seen in a number of figures, but particularly in Figs. 16 and 18, goldfieldite is cut and partially replaced by all gold-silver tellurides and gold. From these figures the intimate nature of the intermixture is apparent. In age, goldfieldite is later than the famatinite-bismuthinite group and earlier than gold-silver tellurides and gold.

Unknown Mineral Intergrowth of Two Minerals.—Sparsely scattered through goldfieldite in ores from Claremont shoot, are

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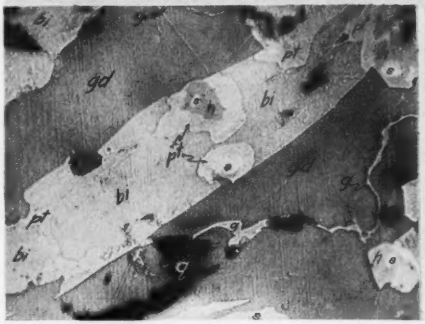
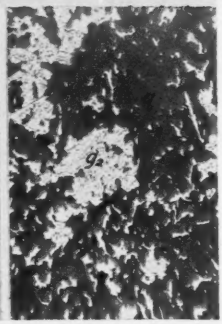
18





19

FIG. 16. Claremont shoot, 1200 level. The white outlined area is yellow gold (g_1). Adjacent to it is red gold with scattered inclusions (g_2). All are set in goldfieldite (gd); the veinlet cutting across the upper left corner is of red gold. Jet black areas are residual gangue (q). × 515.

FIG. 17. Enlargement of piece of red gold (g_2) of Fig. 19; the inclusions are famatinite (f). A small crystal of pyrite (p), in lower center. Black specks within the gold are gangue (q), as is most of the border. Very high magnifications show that the other smaller specks are either famatinite, pyrite, goldfieldite, or gangue. × 610.

FIG. 18. Claremont shoot, 1200 level. Light gray mineral is bismuthinite (bi), partially replaced by sylvanite (s) within darker hessite (h), which is in turn surrounded by gray petzite (pt). This peculiar concentric arrangement, common with these three tellurides, may be interpreted as unmixing. The main areas of goldfieldite (gd) are cut by veinlets of gold (g). Residual patches of gangue (q), jet black. × 154.

FIG. 19. Engineer's lease. Enlargement of a portion of the dark rounded area, Fig. 1. Speckled gray material is red gold (g_2) The thin white needles are a mixture of famatinite, bismuthinite, and goldfieldite, set in quartz (q). Jet black specks associated with ore minerals are alunite. The peculiar forms assumed by the ore minerals are interpreted as pseudomorphs resulting from selective replacement of alunite. This texture has been noted in ores from several leases. × 54.

small, rounded to angular blebs, or irregular, somewhat fibrous-appearing masses of grayish-brown, soft material, isotropic in polarized light (Fig. 16). Close examination shows this substance to be an intimate intergrowth of two minerals, in about equal amounts, one brown or pinkish brown and the other gray. No areas large enough to permit sampling for qualitative tests were seen. Etch tests made under high magnifications do not correspond to those given by Short for algodonite, although they do correspond with those given by Schneiderhöhn for this mineral. Without larger areas and more detailed examination, this determination must be regarded as incomplete and the mineral unknown.

Gold-Silver Tellurides.—Gold-silver tellurides: viz., petzite (Ag_3Au_2Te), hessite (Ag_2Te), and sylvanite (Au, Ag, Te) occur in minute amounts in most of the other ores examined. They are for the most part intimately intergrown with one another and with goldfieldite and/or bismuthinite. As shown in Fig. 18, they have selectively replaced bismuthinite to some extent, but also cut and replace goldfieldite. No age difference between these tellurides and gold could be established with certainty, since the tellurides are deposited in, and out from, the same fractures that contain gold. However, some of the gold appears to be later than the tellurides.

Gold.—One of the most interesting minerals of the suite, from both the economic and scientific viewpoint, is gold. Two distinct types are present, first a bright yellow gold that matches almost exactly with chalcopyrite in color, and second, gold with a distinctly reddish color, similar in appearance to the so-called manganese gold.

The first, or yellow type, is the only gold present in ores from Mohawk mine. Microchemical tests revealed small amounts of silver, which doubtless account for the color. As has been shown, the gold in these ores is confined to veinlets that cut all minerals with the exception of bismuthinite and the gold-silver tellurides. It selectively replaces the older minerals, the order of attack being sphalerite and gangue first, goldfieldite and fama-

tinite later. This type of gold is sparingly present in ores from other mines, notably the Claremont. In the specimen from the 1200-foot level of that mine it occurs side by side with red gold (Fig. 16). In this ore, the gold appears mostly in blebs and veinlets, the blebs having the appearance of swellings on the veinlets, like potatoes on their roots, rather than as typical replacing veinlets such as are shown in Figs. 6–9. Inclusions are rare in this gold, but occasional specks of pyrite, sphalerite, and goldfieldite are noted under high magnifications.

The second type, red gold, is characteristic of all ores with the exception of those from the Mohawk mine. It is particularly well developed in the specimen of Fig. 1, in which yellow gold is not present. Microchemical tests failed to reveal any manganese, and although the test for silver gave negative results, minor amounts of that mineral may be present in solid solution with the gold.

Under the microscope, with moderate magnifications, this gold has a peculiar speckled appearance. With high magnifications, 1000 diameters or more, this speckled appearance is seen to be due to the presence of innumerable inclusions of pyrite, famatinite, goldfieldite, and gangue, as shown in Figs. 17 and 19. Inclusions of famatinite are so numerous and so finely disseminated that, because of their strongly anisotropic character, the gold under low magnifications is apparently anisotropic. The size of the inclusions varies from those easily visible at 265 diameters to those barely discernible at 1750 diameters. Doubtless still higher magnifications would reveal even smaller inclusions. The reddish color is no doubt due in part to these inclusions, but even areas that are apparently free from them have a color distinctly different from Mohawk gold, probably due to a lower silver content. Gradations in color between the two types occur in ores from the Claremont shoot.

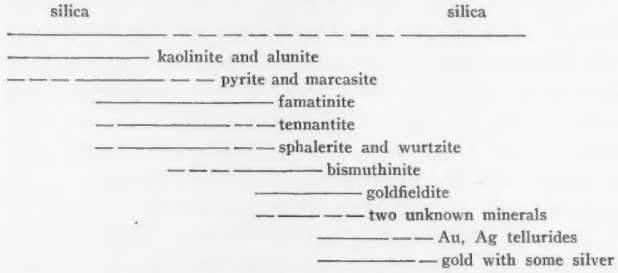
As has been shown above, gold was the last mineral precipitated except quartz and possibly the tellurides of gold and silver. The microscope shows positively that it has replaced sphalerite and gangue to a considerable extent and indicates strongly that it has

replaced goldfieldite and famatinite in lesser amounts. In many cases gold came after previous minerals were not only formed but shattered, following along the many fine, wandering fractures, some of which were to be later reopened and filled with late quartz.

SUMMARY.

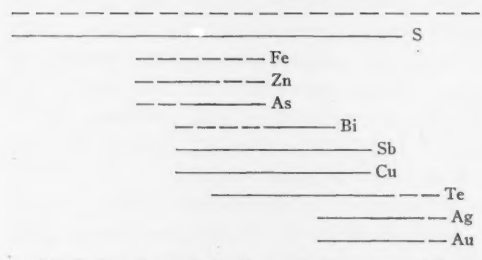
In general, these ores show a normal sequence of mineralization. The first step in the development of the deposits was alunitization, kaolinization, silicification, and pyritization of the country rock, widespread throughout the region but most intense

TABLE II.



Age relations of Goldfield minerals. Full lines, well established periods of deposition; dashed lines, doubtful periods of deposition. Supergene minerals disregarded.

TABLE III.



Periods of precipitation of elements, either combined or native. Full lines, well established; dashed lines, doubtfully established. Supergene deposition disregarded.

along relatively restricted channels that became ledges. Next, solutions carrying the ore minerals rose up through certain selected ledges, the reason for the selection not being understood. Tennantite, famatinite, sphalerite, and bismuthinite were first deposited; that is, the solutions carried copper, arsenic, antimony, bismuth, sulphur, some zinc, and a little iron. Then the solutions ceased to carry zinc, iron, bismuth, and arsenic, and these earlier minerals were no longer deposited. On introduction of tellurium into the ore-bearing solutions, this element with copper, antimony, and the remaining sulphur combined to form goldfieldite. Only after the solutions became completely free from copper and antimony, were gold and silver introduced, combining in minor amounts to form tellurides, but mainly deposited in a myriad of veinlets, both as fracture fillings and as metasomatic replacements of earlier minerals. Finally, silica was deposited in veins cutting through, and as crusts coating, all previous minerals, closing the period of hypogene deposition. This succession of minerals is graphically shown in Table II, the succession of elements in Table III.

ACKNOWLEDGMENTS.

The authors are indebted to Mr. C. D. Woodhouse for the specimens of rich ores submitted by him. They wish to thank also Dr. A. F. Rogers, who read the manuscript and offered many helpful criticisms, Professor Adolph Knopf, who first directed the authors' attention to the occurrence of wurtzite in this district, and Professor Alan M. Bateman, in whose laboratory the final steps in the investigation were completed, and who checked the identification of the wurtzite.

STANFORD UNIVERSITY,
CALIFORNIA.

THE "TERRA ROXA" IN SÃO PAULO, BRAZIL.[1]

FRED. W. FREISE.

FOUR-FIFTHS of the coffee plantations of São Paulo, Brazil, are located in the Terra Roxa, an area the fertility of which is recorded in nearly all publications dealing with agriculture in the State. Investigations have been carried on over a period of twenty years concerning some of the more important details of rock disintegration and soil formation, in order to determine the specific conditions on which this fertility depends.[2]

GEOLOGY OF THE REGION.

With the exception of a small Permian area in the south part of the State, the rocks underlying the Terra Roxa are of Triassic age. They are coarse-grained gray or yellow (Botucatú) sandstones cemented chiefly by silica, with a total thickness of about 1800 feet. In numerous places diabases cut across or are intercalated with these sandstones; two periods of intense Triassic volcanism occur, one shortly after the beginning of the sandstone deposition, the other towards its close. Of this younger diabase, only small areas escaped the deep pre-Cretaceous erosion. Of the older diabase, about 6,100 square miles is exposed; about 5 per cent. of this area is cultivated. This part of the territory constitutes what is called "Terra Roxa Apurada" (genuine Terra Roxa) and that part where only the disintegration products of the diabase and the former sandstone formation are found is known as "Terra Roxa Mixta" (mixed Terra Roxa).

[1] Revised by Dr. E. L. Bruce and the Editor.

[2] The native name Terra Roxa is derived from the Italian *terra rossa*, red soil. This name was given by the first foreign colonists, who settled in the State of São Paulo about 1850. It is a misleading term, since *roxa* means purple in the Portuguese language, but as it is in general use in literature, it will be adhered to in this paper.

This portion amounts to about 55,000 square miles, or 55 per cent. of the total area of the State. Forty-five per cent. of this surface is still covered with virgin forest; 17.2 per cent. is under cultivation.

The Cretaceous system, with which this paper is not concerned,

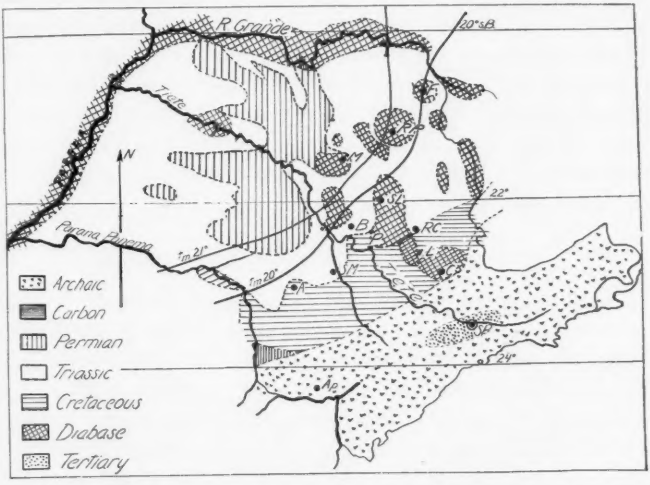


FIG. 1. Geological map of the State of São Paulo, Brazil. Geography (from N. to S.): *I*, Igarapava; *F*, Franca; *Rp*, Ribeirão Preto; *M*, Mattão; *Sc*, São Carlos do Pinhal; *B*, Brotas; *RC*, Rio Claro; *P*, Piracicaba; *L*, Limeira; *C*, Campinas; *Sm*, São Manoel; *A*, Avaré; *Sp*, São Paulo; *Ap*, Apiahy.

Tm 20 = curve of the medium annual temperature of 20° C.
Tm 21 = same, of 21° C.

consists of sandstones with some conglomerates. The average thickness is 950 feet.

Climatic Factors.—The territory studied is a table-land, 1,900 to 2,700 feet above sea level, sloping gently to the northwest. The average temperatures range from 17° to 20.7° C. The absolute maximum is 38.4° C. and the average of the highest temperatures is 29.5°. The annual rainfall is 1,100 to 1,480

mm., distributed over 120 days; 77 to 88 per cent. of the rain falls from October to March or April. A considerable amount of moisture, not registered by the usual pluviometers, comes from dew and fog, and should be credited to the total precipitation of the dry or winter months; according to careful measurements made by the writer over long periods, this moisture corresponds to 70 to 120 per cent. of the precipitation registered by pluviometers during the dry season, and the number of rainy days increases 40 to 55 per cent. from the end of May to the second half of August. Evaporation amounts to 80 to 90 per cent. of precipitation. The climate is therefore moderately moist and moderately hot, with little variation in temperature and average precipitation between the seasons.

PETROGRAPHIC AND MINERALOGIC DETAILS.

The diabases are black rocks composed of lime-soda feldspar and pyroxene with very little apatite, some magnetite, and more abundant titanite, as accessories; near São Manoel and Piracicaba they are distinguished by orthorhombic pyroxene, olivine, and quartz. The analytical differences are insignificant; the extremes of composition may be given in percentages as follows: SiO_2, 45.92–52.36; Al_2O_3, 10.62–13.16; Fe_2O_3, 0.52–8.65; FeO, 3.87–9.33; TiO_2, 0.23–1.14; MnO, 0.04–0.44; MgO, 3.53–6.28; CaO, 5.61–10.94; Na_2O, 1.44–3.16; K_2O, 0.32–1.62; P_2O_5, 0.18–0.47; CO_2, traces–0.13; H_2O, 1.33–2.72. The specific gravities lie between 2.884 and 3.162.

Most of the pyroxenes show no unusual composition but some specimens found at Limeira have a rather high content of manganese. Their analysis gave the following results in percentages: SiO_2, 49.39; TiO_2, 0.28; Al_2O_3, 3.77; Fe_2O_3, 2.26; MnO, 9.22; MgO, 16.02; CaO, 14.81; Na_2O and K_2O, 1.34; loss on heating, 0.74; total, 99.96. Spec. Gr., 3.386.

Among the accessories is an unusual violet-colored apatite in thin columnar crystals, which contains 91.25 per cent. $Ca_3(PO_4)_2$ and 8.03 per cent. CaF_2, with 0.42 per cent. $(FeMn)_3(PO_4)_2$, and no chlorine.

Large cavities occur in the diabase effusions of the Serra do Itaquery near Piracicaba. In them is a mineral isomorphous with apophyllite ($CaO.(SiO_2)_2.2H_2O$) in which up to 33 per cent. of the Ca is replaced by Mn; a variety of comptonite with considerable fluorine and with partial substitution of K for Na. Desmin, chabazite, and delessite are also found. Agate occurs near Rio Claro, and opal near Rio Claro, Limeira, and Araras.

ROCK DISINTEGRATION.

The different stages of rock disintegration may best be observed in the districts still covered with virgin forest in the northwestern part of the State, where the horizontal or slightly inclined plateaus are cut by the numerous water courses that form the Paraná River system.[3] Profiles such as shown in Fig. 2 are

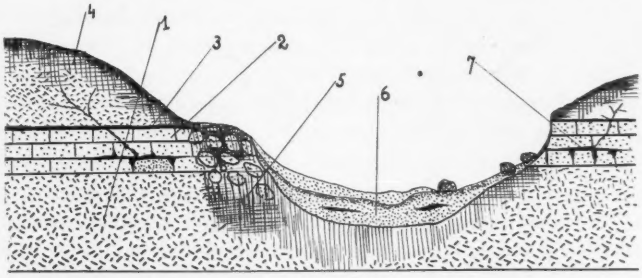


FIG. 2. 1, Diabase; 2, Botucatú sandstone; 3, Clay cover; 4, Terra roxa on original site; 5, Terra roxa mixed with débris of (2); 6, Terra roxa from (4) and (5); transported, with layers of "Ortstein"; 7, Silification by underground water.

common. The average depth to fresh rock is 35 to 55 feet; towards the northwest this distance increases. Where the depth of disintegrated material is greater than this maximum, it is due to transportation of débris from adjacent areas. In no part of the region underlain by diabase is the depth of disintegrated rock

[3] The larger plateaus are called *chapadão,* the smaller ones *chapadas;* softly rounded hills only a few hundred square meters in area are designated *chapeo de sol* (umbrella).

as great as is commonly found above Archean granites and gneisses in Brazil (120–150 feet).

The first phases of disintegration in the diabase can be measured only on rock surfaces too steep to permit accumulation of detritus. Pits of microscopic size are produced by the organic acids of various lichens; the surfaces of the plagioclases acquire a milky color, pyroxenes become rusty or brown, and the rock becomes stained. During the dry season, the small fissures are filled with gray-brown carbonate accompanied by a more or less important residue of silicate; when not recognizable under the microscope, this is indicated by analyses, which show that the quantity of CO_2 is not sufficient to satisfy all the bivalent bases present. Calcium is removed more rapidly than magnesia, silica is transported early, as is shown by the existence of films or veins of opal in underlying cracks. Most of the reactions take place with increase of volume. Analyses show that in the plagioclase, increase in volume is directly proportional to formation of $Al(OH)_3$ and of carbonates; sodium is removed more rapidly than calcium and disintegration products free from sodium may still retain almost wholly the original calcium content. Plagioclases rich in albite (*e.g.* those of Araras) disintegrate more quickly than those with a greater percentage of anorthite.

Compared with the chemical changes above-mentioned, the effects of solar heat are rather insignificant, although daily changes in temperature may range from 30° to 35° with a surface temperature as high as 70° C. The irregularity in arrangement of the several components is the chief reason why expansion does not produce cracking or fissuring such as occur commonly in granites due to their large orthoclase crystals, or in gneisses with their pronounced parallelism of constituents.

Where an extensive covering by finely distributed moisture (dew or mist) frequently and regularly takes place, the quantity of detritus mechanically eroded may be figured as being 1.3 to 1.80 Kg. per square meter annually. Systematic analyses of ground waters show that the amount of rock constituents dissolved is about .450 to .750 Kg. per square meter annually.

Where vegetation consists of plants higher than lichens or mosses, the disintegrated rock substance may amount to three to five times these figures. Where the slope of the rock surface is more than 38 to 42 degrees, the débris, if sufficiently wet, moves slowly downward and there is a natural classification of the components according to grain size and specific gravity. There is thus an increase in porosity which favors greater ease of cultivation and the penetration and expansion of plant root-systems. In contrast, the residual deposits are comparatively compact and are rich in silica deposited from the descending waters. Where humus is included in the transported material the deposits are dark in color and are called *massapé*.

Sections of disintegration products from 15 to 80 feet thick are available where wells have been excavated.

In long-continued rains falling at a rate of 2 to 6.5 mm. per hour, the rain water at temperatures of 17.5 to 22.4° C. contains 7.5 to 33.55 cubic cm. of CO_2 per liter; in floating mists which contain 35 to 55 Gm. of water per cubic meter of air, 66 to 80 cu. cm. of CO_2 and 1.55 to 13.50 cu. cm. of HNO_2 were found per liter. The rain water as it sinks underground also acquires further amounts of CO_2 from root expiration. A grass cover with a dry weight of about 400 to 650 Gm. per square meter produces, from 100 Gms. (dry weight) of root substance, 11.55 to 32.55 Gm. of CO_2 in twenty-four hours; full-grown virgin forest cover produces by root expiration into the soil atmosphere a quantity of CO_2 that may be estimated at 110 to 250 Gm. per square meter in twenty-four hours. Considerable quantities of this CO_2 do not reach the rock surface so as to become active as a decomposing agent; but analyses of free-running underground water show the following quantities of CO_2 in cubic centimeters per liter; 38 per cent. of the waters contain 10–15 cu. cm. per liter; 31 per cent., from 15.01 to 20 cu. cm.; 14 per cent., from 20.01 to 25 cu. cm.; and 17 per cent., more than 25.01 cu. cm.

All underground water in virgin forest districts contains lactic acid—a fact that apparently has not been mentioned in literature dealing with rock weathering. Percentages varying from 0.72

to 2.23 were found in untouched virgin forests, and even in soil freed from the old roots in a coffee plantation, the water contained 0.09 to 0.20 per cent. lactic acid, which probably results from the fermentation processes undergone by mucilaginous constituents of decaying roots due to the activity of fungi; it seems to be stable only at levels where oxygen is absent or in small amount, since in the presence of oxygen it is readily decomposed with development of CO_2 and H_2O. What proportion of the lactic acid reaches the rock surface cannot be determined. If it is assumed that 1.20 kilos of root substance containing not more than 5 per cent. of fermentable constituents decays by fungal activity each year, the fermentation products being calculated as 50 per cent. of those theoretically possible, 300 grams of acid would be produced per square meter annually. This quantity obviously must be distributed through a considerable volume of soil. As far as laboratory tests may be assumed to indicate actual underground conditions, it seems that the lactic acid is of major importance as an activator of decomposition. Under its attack the cations yield in the following order: K, Na; Fe, Mn; Mg, Ca, Ba; Al. The clouded or wax-like films on larger crystals of plagioclase are more commonly lactate than colloidal Al_2O_3; pyroxenes attacked by the acid develop an intricate wrinkling or network of microscopic furrows.[4]

Most of the sections examined consist neither of alumina hydrate nor of material of the composition of kaolinite. They are made up of mixtures of the two in varying proportions. When the analytical data are co-ordinated with the underground water distribution arising from natural configuration and former or present vegetative covering, the following conclusions may be drawn: *Where and when an abundant supply of ground water is present, the composition of the final products of disintegration of diabasic rocks in the area examined is alumina hydrate; where the water supply is moderate and contains humus in suspension, the*

[4] When prisms of diabase were submitted to a 1:500 solution of lactic acid, within 36 hours distinct elimination of alkali, iron, and calcium could be observed, and in a 1:1000 solution, 13.50 per cent. of the alkali, 3.82 per cent. of the iron, and 0.67 per cent. of the calcium content went into solution within a lapse of 32 days.

rock shows alteration to kaolinic substances. The zone of exclusive alumina hydrate decomposition coincides with the territory where the annual rainfall is notably higher than 950 mm.; districts with less rainfall belong to the zone of kaolinic alteration; in regions with an annual rainfall of more than 950 mm., possibly up to 1,500 mm., kaolinic decomposition is found only where constant and vigorous activity of waters charged with humous suspensions occurs, e.g. *in accumulating hollows or shallow valleys; districts with more than 1,500 mm. of annual precipitation have alumina hydrate as the final result of diabase decomposition.*

The scanty local geological literature usually applies the term "laterite" to the final products of the series of processes discussed here; the author prefers not to use this term, since the material is not genuine laterite. Furthermore, a porous, concretionary, or scoriaceous structure is nowhere sufficiently developed to justify the term "laterite."

Concretions.—At Araras, Rio Claro, and São Manoel, a stratum 50 to 80 cm. thick, distant 1.5 to 1.8 meters from the solid surface of the diabase, is composed of concretions of pea- to cherry-size, around nuclei of pyroxenite, rutile, or rarely quartz; most of these concretions are spherical, with smooth or slightly rough surface, vivid red in color, and moderately hard when moist; but when dry the hardness increases to that of quartz, and the spheres shrink slightly. From the center to the surface, these spheres are composed of layers 0.05 to 0.2 mm. thick, of hydrate of alumina, chalcedony, hydroxide of iron (and manganese), and rarely carbonate of calcium and magnesium. In strong underground solutions these concretions are rapidly dissolved; cementation of the concretions was observed at only three points. The composition of the cement is: $Al(OH)_3$, 80 per cent.; SiO_2, 15.8 per cent.; $CaCO_3$, 4.2 per cent. The following table gives the composition of these concretions.

A similar bed of concretions, the size of walnuts and with a considerable amount of iron, has been found near Cravinhos, in the district of Ribeirão Preto; these concretions have the follow-

TABLE I

	Not Cemented —from Araras	Cemented—from Rio Claro	Decaying—from S. Mancel
$CaCO_3$	43.48 per cent.	42.15 per cent.	21.32 per cent.
$MgCO_3$	2.66 per cent.	4.18 per cent.	2.13 per cent.
Kaolin	8.88 per cent.	12.62 per cent.	4.17 per cent.
$Al(OH)_3$	7.73 per cent.	18.14 per cent.	11.55 per cent.
SiO_2 crystallized or amorphous	16.22 per cent.	11.05 per cent.	18.36 per cent.
Fe_2O_3	11.26 per cent.	6.37 per cent.	7.15 per cent.
MnO_2, TiO_2	.03 per cent.	traces	.06 per cent.
H_2O	9.71 per cent.	5.50 per cent.	32.89 per cent.
CO_2	.....	.....	12.33 per cent.
Totals	99.97 per cent.	100.01 per cent.	99.96 per cent.

ing composition: Fe_2O_3, 26.82 per cent.; Al_2O_3, 18.66 per cent.; SiO_2, 28.92 per cent.; $CaCO_3$ and $MgCO_3$, 16.42 per cent.; MnO_2, 1.55 per cent.; TiO_2, 0.52 per cent.; P_2O_5, 0.38 per cent.; moisture, 6.63 per cent. Total, 99.90 per cent. These beds are not considered to be true laterite.

At several other places concretions of greater dimensions have been formed where waters heavily charged with dissolved rock material entered sandstones of the Botucatú series; at various times such beds have attracted economic attention because they were considered equivalents of, or substitutes for, bauxites. However, they are merely sandstone lumps cemented by silica and hydrates of iron and alumina; many of these masses have a regular arrangement of zones of varying thickness or carry as cement introduced material that replaces the original calcareous or argillaceous cement. In some instances these beds are of a deep red color and the surface of the blocks has cellular structure that resembles laterite. The natives call them *canga* (heads), but this term should be applied only to the well known conglomerates of the central part of the State of Minas Geraes, which are composed of several iron minerals with a siliceous or mineralized cement containing gold and diamonds. These concretions have the following composition: SiO_2, crystallized or amorphous, 22.50–32.85 per cent.; Al_2O_3 in hydrate or silicate of Al, 38.10–51.65 per cent.; Fe_2O_3, 24.25–30.33 per cent.; $CaCO_3$ and $MgCO_3$, 10.50–14.25 per cent.; TiO_2, 0.58–1.44 per cent.; man-

ganese as coloring substance; gold (only four samples out of 25 examined), 3.50–4.15 grams per ton.

Bauxite.—Whether commercial quantities of alumina hydrate, *i.e.* genuine bauxite, occur in the territory studied is still questionable; one place only, the neighborhood of Ribeirão Preto, was examined a number of years ago for this mineral, and several isolated masses were discovered with thicknesses varying from 2 to 4 feet and surface areas of 250 to 500 square yards; the deep-red or brown fillings proved to be of varying composition and it seems that they are introduced. The composition is: Al_2O_3, 39.68–58.28 per cent.; Fe_2O_3, 5.18–11.63 per cent.; SiO_2, 4.44–14.86 per cent.; TiO_2, 0.16–2.35 per cent.; CaO and MgO, 0.11–0.48 per cent.; K_2O and Na_2O, traces–0.91 per cent.; H_2O, 23.36–32.63 per cent.; P_2O_5, 0.05–0.25 per cent. The oxides of Ca, Mg, K, and Na seem to be present in secondary silicates. This material is harder than bauxite from other localities and attempts to utilize it have been unsuccessful.

In some places greater amounts of alumina hydrate are consolidated in the form of benches 3 to 5 inches thick and some square meters in extent, which in some features are similar to the deposits known as "Ortstein." They differ from genuine "Ortstein" in their complete lack of humic constituents; they fix for periods of undetermined length a great part of the iron oxy-hydrate content circulating underground, and seemingly are due to the activity of bacteria. The following is an average of a series of analyses: SiO_2, 55.37 per cent.; Al_2O_3, 10.62 per cent.; Fe_2O_3, 18.44 per cent.; MnO, 0.11 per cent.; CaO, 0.17 per cent.; MgO, 0.44 per cent.; K_2O and Na_2O, 4.52 per cent.; P_2O_5, 0.16 per cent.; CO_2, 2.88 per cent.; moisture, 7.32 per cent. Total, 100.03 per cent. They offer great resistance to the penetration of small roots; they are, however, eagerly searched for by the suctorial roots of cultivated plants because they contain considerable amounts of nutritious matter; they can easily be broken up by strong subsoil cultivators or similar implements.

Kaolin.—As stated above, conditions for the formation of kaolin are confined to zones of moderate supply of underground

waters charged with humous substances; for the formation of alumina hydrate abundant water supply is necessary. There seems to be a contradiction in this, since abundant water may be expected only in virgin forest districts where the greater part of the precipitation is readily absorbed and the humous content of the water is likely to be far greater than in regions where most of the rainfall passes immediately into the rivers. It must be borne in mind, however, that the forests of the territory examined are not dense, having only 75 to 90 tons of organic surface substance per acre; 6 to 8 per cent. of this decays annually and 80 to 90 per cent. of it, *i.e.* everything except leaf veins and bark, is transformed by fermentation processes into gases; even in hollows favorable for accumulation of humus, 1.75 per cent. is exceptionally high.[5]

Genuine kaolin is found only near São Manoel; with 38.8–39.5 per cent. of Al_2O_3 and 45.8–46.5 per cent. of SiO_2, it corresponds exactly with the theoretical formula; material elsewhere that resembles kaolin consists of solidified colloids of alumina silicate of varying composition. No deposits of economic value have yet been discovered.

PHYSICAL AND CHEMICAL SOIL CONSTITUTION.

The thickness of disintegrated soil is everywhere more than 12 feet; in this depth, layers of one foot thickness each were separately examined. The different parts of the territory examined show only slight differences in composition; therefore the results may be assembled as shown in Table II.

The material was sized by the Atterberg-Appiani sedimentation process, the classes being those of Atterberg, *i.e.* coarse sand 1–0.1 mm., fine sand 0.1–0.05 mm., coarse clay 0.05–0.01 mm., medium clay 0.01–.002 mm., fine clay inferior to .002 mm.

The coarse sand has its maximum in the 4th and 5th foot of

[5] Only four streams in São Paulo are indicated as dark in color by the terms "rio" (or "ribeirão"), "preto," "negro," "pardo," or "agua preta." In Minas Geraes, in an equal area underlain by Archæan rocks, there are nineteen dark-colored streams. The fact is that the ancient terminology has now lost significance because deforestation has diminished greatly the transportation of humus by rivers.

TABLE II

Depth in ft.	Physical Composition of Humus-free Soil, Dried, at 110° C.					Amount of Some Chemical Nutrients, Soluble in 10 per cent. HCl			
	Sand		Clayey Matter						
	Coarse	Fine	Coarse	Medium	Fine	CaO	P_2O_5	MgO	K_2O
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
1	25.12	24.22	9.06	14.92	26.68	.066	.031	trace	.035
2	27.55	20.62	10.09	14.86	26.88	.072	.028	trace	.028
3	31.63	18.55	8.06	12.30	29.46	.042	.035	.077	.031
4	32.28	16.82	8.21	9.54	33.15	.088	.056	.092	.048
5	31.81	22.77	7.40	7.90	30.12	.092	.061	.135	.062
6	30.06	26.22	5.58	7.68	30.46	.148	.082	.185	.077
7	30.42	32.01	9.03		28.54	.142	.056	.167	.025
8	29.15	35.82	6.67		28.36	.131	.038	.156	.015
9	27.62	25.05	5.02	7.00	25.31	.129	.108	.145	.017
10	28.05	37.22	10.58	12.78	21.37	.126	.306	.137	.036
11	28.22	37.18	6.43	10.04	18.13	.132	.195	.128	.034
12	27.62	40.66	4.22	8.26	19.24	.136	.133	.117	.026

soil profile and decreases in deeper layers by 8 to 12 per cent.; it consists mainly of milky opal with a dark red coating of oxyhydrate of iron or more rarely of humic substances; grains of magnetite, titanic oxide, chromite, and zirconite, are rare. The fact that the percentage of this coarse sand in the soil is almost constant throughout the layers insures a high water capacity and facilitates the ascension of mineral solutions in the dryer seasons. The percentage of fine sand decreases to depths of 4 or 5 feet, below which it increases. In 70 per cent. of the samples the clay portion increases down to a depth of 3 or 4 feet, and these samples correspond to places where improper agricultural treatment, principally the annual burning of the vegetative covering, has permitted mechanical transportation of this material downward. The remaining 30 per cent., in which clay decreases with depth, correspond to areas where the original soil covering still remains as virgin forest, or where no detrimental erosion of fine soil has taken place. This latter area is being reduced every year by the use of obsolete agricultural methods, and it is probable that within a few decades nothing will be left of the famous fertility of the São Paulo *terra roxa,* the porosity of the fine soil being replaced

by a density and compactness that will be expensive, if not impossible, to overcome.

The apparent specific gravity lies between 1.237 and 1.353, the real specific weight between 2.655 and 2.783, the average porosity, 47.6 per cent., the maximum water content, 26.75 per cent.

Chemical nutrients, as soluble in 10 per cent. HCl, are given in Table II. Lime occurs in small amount down to a depth of 5 feet; below that level it remains almost constant, but never in large amount. Almost 90 per cent. of it is silicate. Phosphoric acid has two maxima, one at a depth of 6 feet, the other at 10 feet; a small amount of it is in combination with lime, the greater part with alumina and iron. Magnesia, present only in traces in the upper 2 feet, increases to a maximum in the 6th foot of depth and decreases regularly downward. The amount of potash, very insignificant in the first 3 feet of depth, shows a slight increase to a depth of 6 feet and rapidly decreases below that point. The amount of humous substances is remarkably low even in soils that have been protected against transportation by water; more than 1.2 per cent. is exceptional.[6] The total amount of nitrogen is nowhere greater than 0.44 to 0.88 per cent.

Thus, the *terra roxa* is chemically a poor soil, since some of the most important nutritive elements are present only in very small amount; the fact that during the last 60 to 80 years the plantations have been able to produce very considerable crops is due entirely to the physical properties of the soil, which allow ready penetration of atmospheric constituents and easy growth of roots, and facilitate culture even by primitive implements. Although the soil is clayey, it is warm, since its intense red color results in considerable absorption of solar heat.

[6] According to the figures given above for amount of annual decay in virgin forest such as those of this territory, not more than 40 to 70 grams of humous matter per square meter is available annually to satisfy the needs of growing vegetation; of the root substance, the amount of which may be estimated as about 19 tons per 10,000 square meters, about 60 per cent. disappears entirely through fermentation, and a soil prism 3.60 meters in dimension, about 4,700 Kg. per square meter, receives not more than 0.75 Kg. of residual nutritive matter.

SUMMARY.

Under climatic conditions of moderate warmth and favorably distributed moisture, the disintegration of diabasic rocks has formed, in a large part of the Brazilian State of São Paulo, a deep soil which, although poor in nutritious elements, is of great agricultural value on account of its physical qualities. The rock disintegration forms alumina hydrate, and also genuine kaolin. Each of these is confined to certain localities with definite atmospheric conditions. Oolitic beds are characteristic in many parts of the region, and the formation of such oolites may be observed even at the present time. The "terra roxa," however, is not a true laterite.

RIO DE JANEIRO,
BRAZIL.

THE IRON ORES OF MINAS DEL RIF, SPANISH MOROCCO.[1]

ARNOLD HEIM.

General Information.

The Minas del Rif are the most important modern iron mines of the Mediterranean. They are situated 20 Km. southwest of the modernized harbor city of Melilla, and are reached from there via Nador, by motor car (30 Km.). A mining railway to Segangan, at the foot of the iron mountain Uixan (696 meters), is in operation. The ore is brought down to the railway by cableway (3 Km.). This cableway is now being replaced by an electric railway.

The Compañia Española de Minas del Rif is a strong company working with modern machinery and employing first-class engineers, under the direction of an American, Mr. Spoor. Mining is now done by open cut, but underground work is planned for the future. The main ore body is worked by numerous levels about 25 meters apart. Holes 6 to 8 inches in diameter are drilled by hand to a depth of 25 meters for blasting; the boulders are drilled by air drills and bulldozed. About six million tons of ore have already been developed.

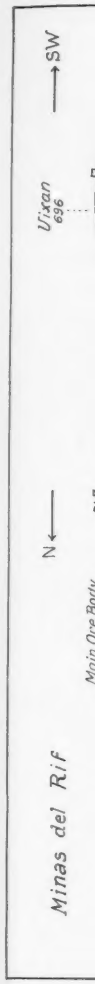
Good native labor is available for 4 to 5 pesetas per day, and Europeans receive 7 to 8 pesetas. Until 1928, 3,000 to 4,000 laborers were employed.

Ore shipments before the world crisis were 2,500 tons per day, but new installations now give a capacity of 5,000 tons daily.

The Ore.

The ore of Minas del Rif is a massive, dense, bluish hematite. Its average composition is:—Fe, 60 to 64 per cent; SiO_2, 6 per

[1] Presented before the Society of Economic Geologists, 13th annual meeting, Princeton, N. J., July, 1933. Introduced by E. S. Moore.



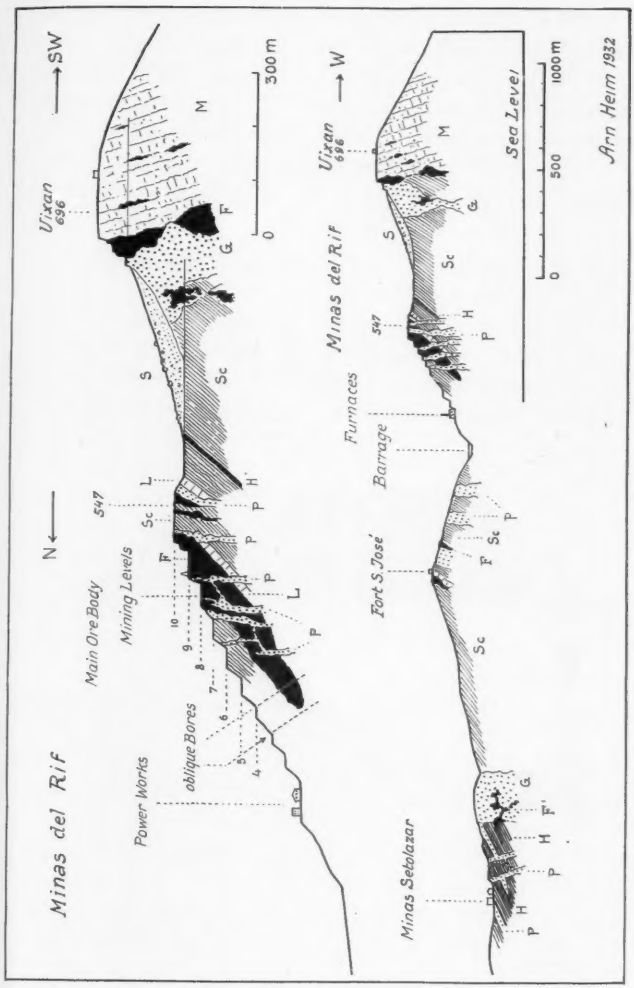


FIG. 1. Section of Minas del Rif and Setolazar, 20 Km. SSW. of Melilla. *F*, iron ore (hematite), magmatic, black; *F'*, same with magnetite; *H*, sedimentary hematite; *G*, granodiorite; *P*, younger igneous intrusives; *M*, marble (Paleozoic ?); *Sc*, schists; *L*, calco-siderite with "limonite"; *S*, secondary iron ore; Nos. 4–10, surface mining levels.

cent; S, 1 to 3 per cent. The sulphur occurs in the form of small pyrite crystals irregularly distributed. A smaller part of the ore, separated by hand, is calcinated before shipment. Six old furnaces and a battery of eight modern furnaces are used. The ore is heated at 800° C. for ten to twelve hours. Only a small amount of coal is necessary, since the pyrite itself yields most of the heat. After roasting, the hematite contains less than 0.1 per cent sulphur.

The Ore Bodies.

The highest ore body (Fig. 4) is exposed at the east side of Uixan (696 M.), where there is a conical hill composed of marble, which dips 70° SW. (Figs. 1, 2). Massive hematite lies between this marble and a weathered fine-grained igneous body (granodiorite), and is about 20 meters thick. The marble at the contact with the ore is extremely coarse-grained, being composed

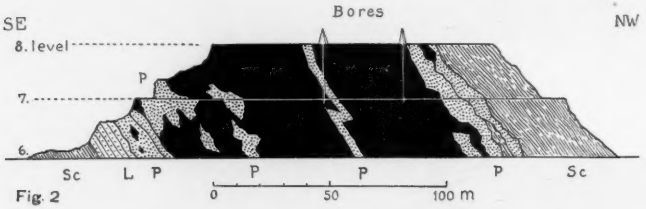


Fig. 2

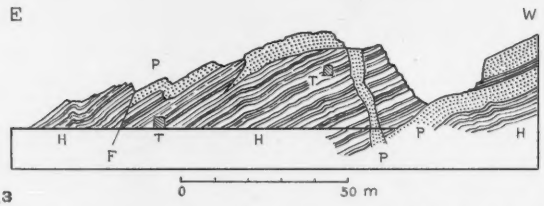


Fig. 3

Fig. 2. Detail of main ore body, Minas del Rif. Black is massive hematite; *Sc*, schist; *L*, sidero-calcite with limonite; *P*, younger intrusive silicates (porphyrite).

Fig. 3. Detail of Minas de Setolazar, northern part. *H*, sedimentary hematite, interbedded with schist; *P*, younger intrusive silicates, dikes and sills (porphyrite); *F*, fault; *T*, mining galleries.

of large calcite crystals. The igneous rocks, as well as the marble, contain irregular nests of intruded iron ore.

Toward the western side of the next lower hill (547 M.) gray siliceous schists are exposed, which dip about 45° N. Within these schists (level 7) a regularly intercalated bed of impure hematite two meters in thickness is exposed. It is of the same sedimentary type as the ore of Setolazar.

The main ore body is that of hill 547 (Fig. 1). It is tabular in shape, has a width of 150–300 meters, a length of about 350 meters, and a thickness of 30–70 meters, as determined by drilling, thus containing about 15 million tons.

On the east and south sides, the ore body is underlain by a bed, 10 to 20 meters thick, of a yellow, finely crystalline carbonate, apparently siderite and ankerite, partly weathered to limonite. It is probably a product of contact metamorphism. At other places the ore body lies within schists (Fig. 2).

The striking feature of this mine is the numerous dikes that intrude the hematite. Since they are intensely altered, largely to kaolin, they resemble white veins that cut across the massive black iron ore (Fig. 5).

Six similar ore bodies of smaller dimensions are found at Monte Axara (Fort San José), opposite Uixan. They have been tested by boreholes and tunnels, but are not being mined. They form prominent black outcrops, which resist weathering more than the surrounding sedimentary strata and silicate intrusions (Figs. 1, 2).

In addition to these primary deposits, ore bodies of minable secondary ore occur on the east slope of Uixan, where a thick accumulation of "limonite" is found containing numerous blocks of more or less fresh hematite which have fallen from the uppermost ore body. The "limonite" contains only 48–50 per cent of Fe, but is free from sulphur. Unquestionably this secondary ore has been derived from weathering of the primary deposit of Uixan.

Minas de Setolazar.

The concessions of this Spanish company lie to the east of those of Minas del Rif (Fig. 1). They contain large quantities of iron ore of secondary quality and some of first grade. The company also has its own railway.

The main ore is a sedimentary deposit. Hundreds of regular layers of more or less pure hematite are interbedded with shale or schist.[2] The hematite beds vary in thickness from fractions of a millimeter to one or two meters. In places, the stratification is so thin as to resemble a book.

The thickness of this hematite series is over 50 meters, and perhaps over 100 meters. The average dip is 30° E.

Thanks to the kind guidance of Don Fernandez de Caleya. the ore was followed by the writer for 2 kilometers along the southern strike, and it extends much farther. The schist series, however, is so much weathered that excavations are necessary to determine the limits of the ore.

The ore is easily separated from the schist, and averages 50 to 54 per cent Fe. However, it contains so much pyrite that it has to be roasted. This process, however, is said to cost only 1.50 pesetas per ton.

In addition to this sedimentary ore, the concessions of Setolazar contain magmatic ore of the Uixan type. At upper Bokoya (in the southern part) the sedimentary hematite series is intruded on the west side by a wedge of massive hematite containing magnetite, with 62 per cent of Fe. At the quarry, lower Bokoya, hematite with included magnetite occurs in the form of blocks and nests inclosed in an igneous silicate body (Fig. 2).

As at Uixan, numerous younger dikes and sills of igneous rocks occur in the vicinity of Setolazar. They contain hexagonal flakes of biotite and appear to be porphyrites and andesites (Fig. 3).

North of Setolazar, the hills are composed of horizontally-

[2] As mapped by A. del Valle and P. Fernández Iruegas (Bol. Inst. Geol. de España, t. XVIII, 1917) the schists east of Uixan are indicated partly as Silurian, partly as Jurassic.

4

5

FIG. 4. Uixan (696 M.), the Iron Mountain, looking up from Segangan to SSE. In foreground at left, the mining railway, in background the iron ore bodies, details of which are shown in Figs. 1–3.

FIG. 5. Surface mining at level 8, looking south. The black rock is compact hematite, the white is kaolinized intrusive. The three derricks are used to drill holes for large-scale blasting. Photographed April 18, 1932.

bedded andesitic tuffs, probably of Miocene age. They are cut and capped by the same type of igneous rocks as those of Setolazar and thus are considered to be of late Tertiary age. These later igneous rocks do not seem to have affected the mineralization, nor have they apparently metamorphosed the adjoining sediments.

Origin of the Ores.

The main bodies of Uixan (Minas del Rif) have the form of magmatic intrusions and are considered to have metamorphosed the adjacent sedimentary rocks. In the writer's opinion, they have been injected in liquid condition similar to igneous rocks and in this respect resemble the great pyrite ore bodies of Huelva.[3] Subsequent to their intrusion, the ore bodies have been cut by the younger igneous dikes.

The main ore of Setolazar is of sedimentary origin, intruded by magmatic iron ore (hematite and magnetite) and later also cut by younger porphyry dikes and sills, which have produced very little, if any, metamorphism of the sedimentary hematite layers.

Both types of iron ore provide great reserves for future development.

The writer realizes that different views of origin are held by other geologists, and invites discussion of this problem.

Zurich, Switzerland.

[3] Heim, Arnold: The Cupriferous Pyrite Ores of Huelva; a Tectonical Sketch. International Geol. Congress, Washington, 1933.

A MICROCHEMICAL METHOD FOR THE DETERMINATION OF BOURNONITE.[1]

R. E. HEAD AND RODGER W. LOOFBOUROW.

THE development of trustworthy methods for the identification of sulphide minerals in polished section has been the object of much experimentation. Although existing methods of microchemical identification may generally be accepted as workable and satisfactory, positive identification of certain minerals still presents considerable difficulty. As an example, bournonite is one of some 200 minerals commonly classified as being grayish-white to lead-gray in color, in polished section. This paper describes a microchemical method that produces a definite surface effect on bournonite and appears to afford a dependable method for its identification.

In the course of a study of the effect produced on various silver-bearing sulphide minerals, it was observed that an acid solution of azolitmin and potassium dichromate produces distinctive effects on bournonite that distinguish it from tetrahedrite, with which it is associated in the Park City mining district. These two minerals are difficult to distinguish on a polished surface and are decidedly difficult to differentiate in the crushed condition when present in concentrates or other mill products.

Several crystals from a Park City mine were used in the work, together with other samples. The crystals had been tentatively classified at the mine as tetrahedrite, but their crystal form indicates that this determination was in error. A chemical analysis of a portion of one of the poorly formed crystals agrees so closely with that given by Dana [2] as to remove any doubt concerning its identity as bournonite. The analyses are:

[1] This paper presents the results of work done under a coöperative agreement between the United States Bureau of Mines and the University of Utah. Published by permission of the Director, U. S. Bureau of Mines (not subject to copyright).

[2] Dana, E. S.: Descriptive Mineralogy. John Wiley & Sons, Inc., New York, 1914.

	Park City Bournonite.	Bournonite (Dana).
	%	%
Lead	42.2	42.5
Copper	13.4	13.0
Antimony	24.7	24.7
Sulfur	20.0	19.8
Totals	100.3	100.0

A further confirmation is the fact that the crystals are orthorhombic, which is the symmetry of bournonite.

Effect Produced.—Etching of a polished section of the crystal of bournonite by an acid-azolitmin-potassium dichromate solution produces a stain that consists of a series of color bands that extend over most of the visible range of the spectrum, blues, greens, and reddish-yellows predominating. The colors are bril-

FIG. 1. Effect of azolitmin on a polished bournonite surface outlining the crystal form of the mineral. × 13 (approximately).

liant, and every portion of the surface is affected. In addition, the bands distinctly outline the crystal form of the specimen, as is well illustrated in Fig. 1.

Preparation of Solutions.—Since azolitmin is not readily soluble in acid solutions, it was found advantageous to dissolve one gram of solid azolitmin in about 20 cc. of water containing 2 cc. of a concentrated (approx. one gram to one cc. of water) KOH solution. After complete solution was effected, the KOH was neutralized with HCl (sp. g. 1.21), 2 cc. excess acid was added, and the solution diluted to 200 cc. The potassium dichromate solution was prepared by diluting a saturated solution, at room temperature, to three times its volume. In making the mixture to be used in staining, three parts of the azolitmin solution to one part of the potassium dichromate solution were used. This mixture seems to deteriorate slowly on standing, and it is considered advisable to use a freshly prepared mixture in making the staining tests.

Application.—To obtain the effect described it was found necessary to expose the polished surface of the specimen to the action of the solution for one minute at 95° C., which is slightly below the boiling point of water at this altitude. This may be accomplished either by immersion of the specimen in a small amount of the reagent in a beaker or by laying it face down in a few drops of reagent in a watch glass. The former method, although slightly more wasteful of the reagent, was found most satisfactory, since it insured a much more uniform application of the reagent during the comparatively long time of exposure. It was found that 10 cc. of the reagent in a 25- or 30-cc. beaker was quite sufficient for the test. Concentration of the solution by evaporation may be avoided to some extent by covering the beaker with a small watch glass.

A study of the time-temperature effects on the reaction showed that the most uniform results were obtained by using a solution at about 95° C. At this temperature it was found that an exposure of five seconds produced a few isolated groups of brilliant blue bands, leaving portions of the surface apparently unaffected and no other colors showing. With a gradual increase of the time of exposure, observations being taken at five-second

intervals, no additional colors were introduced during the first 20 seconds, and the only change in the effect was an intensification of the blue bands produced. As the time is increased from this point, there is a slow development of the other colors. In this development the areas which had been blue during the early stages of the treatment gradually changed through green and yellow to red, suggesting that the effect is due to a slow building up of a film on the surface. The optimum effect under the conditions described above is produced with an exposure of one minute, at which time the entire surface is covered with bands of the various colors. Exposure in excess of 1½ minutes was found to produce a dull yellow film, presumably of lead chromate, which covered the entire surface and obscured the multicolor effect.

The stain produced by the azolitmin treatment is permanent, is not removed or in any way affected by rubbing, and has been found to remain on the specimen for months with no sign of alteration.

Although there is no way of predicting the color that will be produced on an individual grain of the mineral, tests of briquetted materials indicate that one may be assured that the grains will assume one of the above-mentioned brilliant colors, and so far no other mineral has been found to produce an effect which could in any way be confused with it.

In attempting to explain the banded effect there is one possibility which seems to be outstanding—*i.e.*, that this is a case of a "cored" crystal, the various layers that make up the crystal being of slightly different compositions and thus having a slightly different rate of reaction with the reagent. Further confirmation of the test was obtained in a specimen secured from the National Museum through the courtesy of Mr. Wm. Foshag. This specimen, which consists of several well-formed crystals, shows a slight banded structure, the major portion of the surface being a single color.

Application of the azolitmin reagent prepared in the manner described constitutes a distinctive microchemical means for dif-

ferentiating bournonite from other minerals in the group having similar color and chemical characteristics, regardless of slight differences in composition which are suggested by the banding effect produced, as shown by the illustration.

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DISCUSSION AND COMMUNICATIONS

THE PROBLEM OF SERPENTINIZATION.

Sir:—In an article under this caption in ECONOMIC GEOLOGY, November, 1933, H. H. Hess says (p. 649): "The recent work of Keith and Bain shows conclusively that the asbestos veins are fissure fillings, and replacement and recrystallization played very minor rôles in the vein formation."

In making this reference Mr. Hess seems to have overlooked the fact that the conclusions of Keith and Bain were drawn essentially from a study of the "slip-fiber," or deformed, deposits of Lowell Mountain, Vermont, and so are applicable only to deposits of that class. They may be found to apply to the Broughton, or "slip-fiber," phase of asbestos in the mining district of southern Quebec. But this is a minor feature, found mainly along a zone where rock movement is later than, or perhaps causally connected with, the development of oblique and parallel fibers. Any satisfactory theory of origin, therefore, must take due account of the vastly greater deposits of the "cross-fiber" or Thetford phase, which yield, say, 95 per cent. of the whole output in Quebec, and where facilities for observation are proportionally better, both in exposure and preservation of vein structures.

I would also note that under the sub-title, "Distribution of Serpentinization," Mr. Hess has omitted any reference to bands of pure serpentine which border cross-fiber veins with singular regularity. They occur on both sides of the vein and are roughly proportional to it, the band on each side being about three times the width of the asbestos vein. Although the adjacent peridotite country rock is only partially serpentinized, commonly five to twenty-five per cent., these bands are practically pure serpentine. They are better described, with analyses and illustrations of their

relations, in Memoir 22 of the Geological Survey of Canada, 1913, pp. 59–60.

But since serpentine and asbestos are essentially identical in chemical composition, and peridotite alters to serpentine, the question remains a complex one, and its solution still calls for more observation. The word "conclusively" must yet be used sparingly in this connection.

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PETROGRAPHY OF FULLER'S EARTH DEPOSITS.

Sir: In a recent article on the petrography of the fuller's earth of Illinois,[1] brief descriptions of earths from other localities were given, including that from Bath, England. The author stated that "glass shards" were present in this earth and he called it a bentonite. Now this is a very interesting statement, seeing that no evidence of any volcanic activity has hitherto been found in the Jurassic deposits of England, which include the Bath fuller's earth. However, the author's statement is far from convincing.

Actually, what appear at first sight to be glass shards in thin sections of the Bath fuller's earth are platy and angular fragments of a mineral with glassy appearance and low birefringence, which can be concentrated in considerable quantity by carefully washing the material. Chemical analysis shows this mineral to be a variety of feldspar—anorthoclase with a small proportion of lime.

The mineralogical description of the fuller's earth of Bath is of more interest than Mr. Grim indicates. The material contains abundant sphalerite, much of which shows excellent crystal form and occurs in grains up to 0.1 mm. across. Marcasite also is common, often associated with calcite, filling the tests of foraminifera. Other minerals present are, in decreasing abundance, apatite, in broken, prismatic crystals, commonly with good terminations and showing pink or colorless inclusions; zircon, with a

[1] Grim, R. E.: Petrography of the Fuller's Earth Deposits, Olmstead, Illinois. ECON. GEOL., vol. 28, No. 4, pp. 344–363, 1933.

somewhat worn appearance; ilmenite, magnetite, barite, biotite and kyanite. All these minerals are readily obtained by bromoform separation; some of the residues so obtained consist almost entirely of sphalerite and marcasite.

With regard to Grim's description of the Olmstead fuller's earth, the chemical analyses of alleged montmorillonites (Table II) show such large variations that it would be advisable to add analyses of similar minerals, such as kaolinite and halloysite, for comparative purposes. Table III, showing the behavior of "montmorillonite" from Olmstead on dehydration, and Table IV, comparing its X-ray pattern with that of the French mineral, would be more valuable if they also indicated the behavior of the above-mentioned minerals under similar conditions. It is possible that kaolinite and other clay minerals might be "proved" by similar evidence to be montmorillonite.

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REVIEWS

The Deformation of the Earth's Crust. By W. H. BUCHER. Pp. 518, figs. 100, tables 6. Princeton University Press, 1923. Price, $5.00.

Although the author of this volume declares that it was not designed as a text-book, it appears to the reviewer, after a careful reading of its contents, that it is one of the best text-books on structural and dynamic geology for advanced students that has thus far been produced. It is so written that fact and theory are distinctly separated. Facts are formulated in what the author calls "laws," which are generalizations based on observations. The facts on which the "laws" are founded are given by means of illustrations drawn from the publications of geologists in all parts of the world, and on these facts are constructed the generalizations that comprise the "laws." Although there must naturally be some interpretation of the facts before the generalizations can be arrived at, nevertheless the laws are flavored only very slightly with personal bias. The logic of the discussion is such that nearly everyone who reads the book carefully will differ very little from the author's conclusions. Summaries of the facts are given in those cases where their relations are confusing, and in these summaries are outlined what the author believes are their significance. But nothing of theory is mixed in the discussion until it is completed, when there follows an expression of the meaning of the facts in an "opinion." There may be some difference of view as to whether the "opinions," as given, are the only ones logically possible, but the author himself regards them as only tentative. "The facts especially, as formulated in the 'laws,' should be criticized and either recognized or rejected openly by everyone who, by experience and inclination, is in a position to check them against first-hand information in his own corner of the world. In such a way alone can a body of recognized facts be created." "The writer expects his logic and his hypothetical ideas to be scrutinized as severely and, if found wanting, rejected as determinately as he has done with the ideas of others. We can hope to make headway in our search for a road to understanding only by taking the task of critical reasoning as seriously as we take that of accurate observation." "The book comprises an attempt to assemble all essential facts of a general nature that bear on the problem of crustal deformation and to derive

the Arizona Copper Company in 1910 and subsequently adopted at Ray, Miami, Ely, and Braden. The Clay Ore Body at Morenci illustrates the magnitude of the problems that the porphyry coppers presented for mining engineers and the high order of quantitative exactness required in their solution. Diamond drilling proved 379,000,000 tons of 1.02 per cent. ore. The engineers must decide in advance whether to adopt open-cut mining or caving, whether concentration and smelting or leaching. In an operation of the size contemplated an error of 1 ct. per ton on cost estimates means a difference of $875,000.00 in annual profit or loss. For that reason the porphyry copper operations have been called huge manufacturing enterprises.

Braden was the first large copper mine to use flotation, increasing thereby its mill recoveries from 45–55 per cent. to 90 per cent. Inspiration quickly followed with the first large plant in the United States. Miami worked out a 2 per cent. ore body with a minimum mining cost of $1.12. Adjoining it was an ore body with 108,000,000 tons of 0.95 per cent. ore. This was workable if it could be mined for less than 50 cts. F. W. Maclennan worked out on paper a caving system estimated to cost 38 cts. The company spent $2,500,000 to develop the mine, and Maclennan's estimate proved correct.

Chuquicamata is Utah's rival. The reserves of each property are in round numbers 1,000,000,000 tons, but Chuquicamata ores average 2.5 per cent. whereas Utah ores average 1.1 per cent. Chuquicamata installed the first leaching plant, 75 per cent. of the ore is broken with liquid oxygen, and it has the lowest plant cost of production of any. Andes, the youngest of the porphyry coppers, did not grow by piece-meal, as did the rest, but was projected on paper as subsequently built. When production began in 1927, $35,000,000 had been spent on mine and plant. To this $12,500,000 was added in 1928 for a leaching plant.

The narratives of the individual operations are followed by seven chapters on geology, prospecting and estimating ore, power shovel mining, underground mining, concentration, smelting, and leaching.

The chapter on geology points out that not all of this group of deposits are porphyry deposits, nor are all disseminated deposits, but all are low-grade deposits. The chapter gives the range in dimensions of the deposits, in the vertical extent of the leached capping, in that of the oxidized zone, and in that of the zone of supergene sulphides. The maximum vertical range of workings is 2,000 feet at Utah, the maximum depth of leached capping 650 feet at Andes, the maximum vertical range of the oxidized ore 500 feet at Chuquicamata, and the maximum vertical range of supergene sulphides 1,000 feet at Morenci and Braden.

The chapter on prospecting and estimating ore summarizes the results achieved by churn drilling. Carefully organized churn drilling was first

developed at Ray, and it made possible the proving of large tonnages of ore at comparatively low cost and in a very short time. Underground mining checked against churn-drill estimates realized 102 per cent. to 115 per cent. in tonnage, 84.5 per cent. to 91.0 per cent. in tenor, and 86.5 per cent. to 102.4 per cent. in copper content.

The chapter on power-shovel mining describes the developments from the steam shovel on tracks to the electric caterpillar shovel, and shows the accompanying reduction in costs. Block caving methods are described in some detail in the chapter on underground mining. The chapter on milling methods deals largely with the development and application of flotation. The chapter on smelting shows that the period of the porphyry coppers is that in which the blast furnace was superseded by the reverberatory in the treatment of copper ores. The development of the leaching processes, beginning with Chuquicamata in 1916, followed by New Cornelia, Inspiration, and Andes, another of the great achievements of the porphyry coppers, is described in the chapter on leaching.

The last chapter has the title "Building the West" and presents statistically the rôle of the porphyry coppers in the economic life of the western states, as taxpayers, consumers of power, and sources of freight.

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The Geology of Texas. Vol. I: Stratigraphy. By E. H. SELLARDS, W. S. ADKINS AND F. B. PLUMMER. Pp. 1007, figs. 54, pl. 10, map. Univ. of Texas, Bull. 3232. Austin, Texas, 1932. (Distributed, 1933.) Cloth 8 vo. Price, $4.00.

The first volume of the long awaited "Geology of Texas" deals with the stratigraphy of the State to the end of the Pleistocene system. It is a beautiful book, illustrated by handsome plates of fossils, and the reproduction of an excellent aerial photography of a part of the Guadalupe Mountains. In a pocket is a well executed geological map of Texas on the scale 1:2,000,000.

The discussion of each system and each group of systems is introduced by a few general statements. These are followed by descriptions of each formation, including its relation to others, its distribution, etc., and, where deemed necessary, brief statements of reasons for the nomenclature employed and a list of synonyms. Scattered here and there through the text are comments on the underground occurrences of formations where not exposed, on the seas during the times of deposition of the various systems, on the igneous rocks associated with the sediments, and on the structures of individual areas. Every statement is buttressed with references to the

original articles on which the statement is based, and there is a bibliography of 1855 entries. The book is furnished also with a list of theses on Texas subjects that are deposited in University libraries, a subject index of 30 double-columned pages to the bibliography, and one of about 11 double-columned pages to the text of the volume.

The book evidently gives a comprehensive and accurate, but condensed, summary of all that is known of the stratigraphy of the State.

W. S. BAYLEY.

BOOKS RECEIVED.

BY

DAVID GALLAGHER

Geology of North and South McCallum Anticlines, Jackson Co., Colo. J. C. MILLER. Pp. 27, figs. 1, pls. 2. U. S. Geol. Surv. Circ. 5, 1934. Stratigraphy and structure, petroleum and carbon dioxide.

Mineral-Water Supply of Mineral Wells Area, Tex. S. F. TURNER. Pp. 8, pls. 1. U. S. Geol. Surv. Circ. 6, 1934.

Metalliferous Deposits of Greater Helena Mining Region, Mont. J. T. PARDEE AND F. C. SCHRADER. Pp. 318, pls. 47, figs. 36. U. S. Geol. Surv. Bull. 842, 1933. Regional geology; history; geology of mines with production of $176,860,000 in gold, silver, lead, copper, zinc.

Some Mining Districts of Eastern Oregon. J. GILLULY, J. C. REED, AND C. F. PARK, JR. Pp. 140, pls. 8, figs. 21. U. S. Geol. Surv. Bull. 846–A, 1933. Brief regional geology; mines by districts, giving history, production, geology, and probable futures.

Geology and Ore Deposits of Takilma-Waldo and Blue Creek Districts, Oreg. P. J. SHENON. Pp. 53, pls. 14, figs. 5. U. S. Geol. Surv. Bull. 846–B, 1933. Gold-platinum placers, copper lodes, chromite.

Climax Molybdenum Deposit, Colo. B. S. BUTLER, J. W. VANDERWILT AND C. W. HENDERSON. Pp. 42, pls. 15, figs. 5. U. S. Geol. Surv. Bull. 846–C, 1933. History and production, general geology, structure, and economic geology.

Iron Oxide Mineral Pigments of the United States. H. WILSON ET AL. Pp. 198, figs. 34. U. S. Bur. Mines, Bull. 370, 1933. Technology of natural and artificial pigments; U. S. resources by states alphabetically.

Gold Coast Geol. Survey, Annual Report for 1932–33. N. R. JUNNER. Pp. 30. Accra, 1933. Administrative and geologic notes.

Lopinite, a New Type of Coal in China. C. Y. HSIEH. Pp. 16, pls. 2, figs. 2. China Geol. Surv., Fuel Lab., No. 14, 1933. Low moisture and very high volatile content.

Briquetting Illinois Coals without a Binder by Compression and by Impact. By R. J. PIERSOL. Pp. 70, figs. 14, tables 9. Illinois Geol. Surv., Rpt. of Inves. No. 31. Urbana, 1933. Progress report of a laboratory investigation.

Ground Water in Paleozoic Rocks of Northern Alabama. W. D. JOHNSTON, JR. Part II, tables and map. Ala. Geol. Surv. Spec. Rpt. 16, 1933.

Comité Spécial du Katanga, Annales du Serv. des Mines, III, 1932. Bruxelles, 1933. Group of papers on sediments.

New Zealand Geol. Survey, Twenty-Seventh Annual Report. Pp. 21, maps 2. Wellington, 1933. Geological notes.

Geology of Puerto Rico. H. A. MEYERHOFF. Pp. 306, figs. 45, geol. map in color. Univ. of Puerto Rico, Monog. Ser. B, No. 1, 1933. For both geologist and layman; well illustrated.

A Industria Extractiva do Ouro no Estado de Minas Geraes. D. GUIMARÃES. Pp. 54, figs. 9, map. Minas Geraes Geol. Surv. Bull. 1. Bello Horizonte, 1933. Gold extraction; descriptions of mines.

Idaho Mining Industry, 1933. W. H. SIMONS. Pp. 256, figs. 46. Boise, 1934. Statistical; catalog of mines by counties.

Clay Resources of Indiana. G. I. WHITLATCH. Pp. 298, figs. 40. Ind. Conserv. Comm., Pub. 123. Indianapolis, 1933. Technology; production; resources by counties.

Some Aspects of Deep Level Mining on the Witwatersrand Gold Mines with Special Reference to Rock Bursts. W. C. COE ET AL. Pp. 198, figs., pls. Assoc. Mine Managers of Transvaal. Johannesburg, 1933. A group of papers.

Geology of Capetown and Adjoining Country. S. H. HAUGHTON. Pp. 90, figs. 7, pls. 2. S. Africa Geol. Surv., Explanation of Sheet Map 247. Pretoria, 1933.

Geology of the Lower Gwanda Gold Belt. A. E. PHAUP. Pp. 74, pls. 3. S. Rhodesia Geol. Surv. Bull. 24. Salisbury 1933. Descriptive general and economic geology.

Larger Gold Mines of Southern Rhodesia. B. LIGHTFOOT. Pp. 106, figs. 2. S. Rhodesia Geol. Surv. Bull. 26. Salisbury, 1934. Brief history, production, and geology of over a hundred mines.

Silver Yield From Copper Ores and Effects of 64.64-Cent Silver on Value of Copper Ores Produced in U. S. E. W. PEHRSON. Pp. 15. U. S. Bur. Mines, Inf. Circ. 6773, 1934.

Uganda Geol. Survey, Annual Report for 1932. Entebbe, 1933. Geologic notes and map; tin ores.

Copies of books mentioned under "Reviews" or under our "New Book List" (see advertisement page) may be purchased through our Journal Bookshop by writing to W. S. Bayley, University of Illinois, Urbana, Ill.

SCIENTIFIC NOTES AND NEWS

Francis A. Thomson, of the Montana School of Mines, has been appointed head of the NRA work of the mineral division of the Northwest.

J. W. Vanderwilt has resigned from the U. S. Geological Survey and will do consultant work in mining geology and petrology in connection with the Climax Molybdenum Company and the Molybdenum Corporation of America, with headquarters at Denver and Golden, Colo.

George Clothier, formerly resident engineer of the Western Mineral Survey District of British Columbia, has been appointed manager of the Dictator mine, in the Lightning Peak area.

A. Irving Levorsen, of Tulsa, Okla., is now chief geologist for the Tidewater Oil Company, with headquarters at Houston, Texas.

John L. Rich, of the University of Cincinnati, gave a series of lectures on petroleum geology and physiography at Northwestern University in April, in exchange with C. H. Behre, Jr., who lectured at Cincinnati on various phases of economic geology.

H. B. Maufe, Director of the Geological Survey of South Africa, has been awarded the Draper Memorial Medal.

Ralph S. G. Stokes has been elected President of the Geological Society of South Africa.

A. W. Lauer has resigned his position as geologist for the Texas Company, Oklahoma-Kansas-Kentucky division, and is taking up research work in geology.

The Association of American State Geologists held its regular annual meeting and conference with the Federal officials in Washington, D. C., on February 22–23. The officers elected for the coming year are: George C. Branner, Arkansas, President; Arthur Bevan, Virginia, Secretary; Raymond C. Moore, Kansas, third member of Executive Committee.

J. Mackintosh Bell, a graduate of Queen's University and of Harvard University, and well known as a geologist in Canada, New Zealand, England, and the United States, died at his home at Almonte, Ontario, on March 31, aged 56.

C. W. Shannon, formerly head of the State Geological Survey of Oklahoma, died on February 1st at Norman, Okla., aged 55.